Top-Down and Bottom-Up Processes in Vision

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Abstract

To help us efficiently navigate our information-rich environment, the human brain has developed a set of cognitive mechanisms aimed at quickly identifying information that is likely to be behaviourally relevant, collectively referred to as selective attention. Attentional resources can be directed voluntarily, as occurs when we shift attention from one word to the next while reading; or involuntarily, such as when attention is captured by someone unexpectedly entering the room (Yantis, 2000). These two modes of attention are not as independent and clearly distinguishable as once thought (Gilbert & Li, 2013). For example, the extent to which a stimulus involuntarily captures attention is influenced by whether it possesses features relevant to an observer’s current task (the contingent capture hypothesis; Folk, Remington, & Johnston, 1992). Attentional capture is also affected by the level of working memory (WM) load an observer is under (Lavie, Hirst, Viding, & De Fockert, 2004), and by an observer’s WM capacity (Vogel, McCollough, & Machizawa, 2005).

It has been suggested that maintaining top-down biases on attentional capture may require – and compete for – similar neural resources as WM (e.g., Lavie et al., 2004). If so, top-down influences on attentional capture should be reduced (a) when an observer is under high WM load, and (b) in individuals with a low WM capacity. In this thesis these possibilities were tested in a series of seven experiments in which human observers monitored visual stimulus streams for targets defined by a particular feature value (e.g., red). While observers performed these tasks, I took behavioural and electrophysiological measures of attentional capture by distracting visual stimuli that either possessed or did not possess the target feature value.

First I replicated previous evidence for contingent capture. Distractors with the target feature value slowed behavioural responses to concurrently presented targets more than distractors with a non-target feature, consistent with the notion that distractors capture attention more strongly when they possess task-relevant features. Distractors with task-relevant features also evoked a larger N2pc component of the visual-evoked potential, an electrophysiological marker of the covert allocation of visual resources.

I then investigated whether taxing WM reduces contingent capture. An n-back task that required information-updating eliminated the influence of task set on the distractor-evoked N2pc, suggesting that taxing WM compromised top-down biases on early visual processing. There was no such effect on a behavioural measure of attentional capture, however, possibly because taxing WM also compromised the transfer of information from early visual cortex to later stages of processing. A
digit rehearsal task that required only information maintenance did not change the effect of task set on either the N2pc or behaviour. This pattern of results suggests that contingent capture is only reduced by WM load manipulations that place demands on the central executive component of WM (Baddeley & Hitch, 1974).

Next I tested whether high WM load can reduce the effect of task set on even earlier stages of processing than the N2pc, specifically by measuring the P1 component of the visual-evoked potential. Unexpectedly, I failed to replicate a previous finding of an effect of feature-based task set on the P1. Because I found no effect of task set on the P1, I was unable to test whether such an effect was reduced under high WM load.

In a final experiment I examined whether individual differences in WM capacity also influence contingent capture. Previously, Fukuda and Vogel (2011) found that individual differences in visual short-term memory (VSTM) capacity bore no relationship to contingent capture (although such differences did correlate with subsequent attentional disengagement). I set out to extend on this research by testing whether the capacity of the central executive component of WM influences contingent capture. Despite having multiple reliable measures of WM capacity and multiple behavioural and electrophysiological indices of attentional capture, there was no evidence for any relationship between WM capacity and contingent capture.

In summary, I found support for the contingent capture hypothesis that distractors capture attention more strongly if they possess features relevant to an observer’s current task. I found that the task-dependent effect on early stages of processing was reduced when observers were under high WM load, provided this involved information-updating. This suggests that feature-selective mechanisms underlying contingent capture compete for shared neural resources with the central executive component of WM. This reduction in contingent capture did not affect later stages of processing, however, which suggests that taxing WM also compromises the transfer of information from early visual cortex to later stages of processing. Interestingly, I found no evidence for a relationship between contingent capture and measures of WM capacity, suggesting that the competition for resources between WM and feature-based task set only arise when both tasks are performed simultaneously.
Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

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Contributions by others to this thesis

Jason Mattingley and Roger Remington contributed significantly to the design of all experiments reported in this thesis. Jason Mattingley, Roger Remington, and Marc Kamke gave valuable feedback on my interpretation of all results, and on drafts of all writing presented in this thesis. Kristy Butler, Luke Hearne, and Amy Taylor assisted with testing for most reported experiments.

Statement of parts of the thesis submitted to qualify for the award of another degree

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visual feature-based selective attention, contingent capture, working memory, electroencephalography

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ANZSRC code: 170112, Sensory Processes, Perception and Performance, 30%
ANZSRC code: 110906, Sensory Systems, 20%

Fields of Research (FoR) Classifications

FoR code: 1701, Psychology, 50%
FoR code: 1109, Neurosciences, 50%
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<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ADHD</td>
<td>Attention-deficit hyperactivity disorder</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>BESA</td>
<td>Brain electrical source acquisition software</td>
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<tr>
<td>BOLD</td>
<td>Blood oxygen-level dependent</td>
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<tr>
<td>CDA</td>
<td>Contralateral delay activity</td>
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<tr>
<td>EEG</td>
<td>Electroencephalography</td>
</tr>
<tr>
<td>EOG</td>
<td>Electro-oculography</td>
</tr>
<tr>
<td>ERP</td>
<td>Event-related potential</td>
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<tr>
<td>FEF</td>
<td>Frontal eye fields</td>
</tr>
<tr>
<td>fMRI</td>
<td>Functional magnetic resonance imaging</td>
</tr>
<tr>
<td>IFJ</td>
<td>Inferior frontal junction</td>
</tr>
<tr>
<td>IOR</td>
<td>Inhibition of return</td>
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<td>IPS</td>
<td>Intraparietal sulcus</td>
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<td>ISI</td>
<td>Inter-stimulus interval</td>
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<tr>
<td>LCD</td>
<td>Liquid crystal display</td>
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<tr>
<td>LOC</td>
<td>Lateral occipital complex</td>
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<tr>
<td>LTM</td>
<td>Long-term memory</td>
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<tr>
<td>M</td>
<td>Mean</td>
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<tr>
<td>MT</td>
<td>Middle temporal motion processing area</td>
</tr>
<tr>
<td>MVPA</td>
<td>Multi-voxel pattern analysis</td>
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<tr>
<td>N1</td>
<td>An early negative component of the visual evoked potential</td>
</tr>
<tr>
<td>N2</td>
<td>An early negative component of the visual evoked potential</td>
</tr>
<tr>
<td>N2pc</td>
<td>N2 posterior contralateral component of the visual evoked potential</td>
</tr>
<tr>
<td>NTC</td>
<td>Non-target-coloured</td>
</tr>
<tr>
<td>P1</td>
<td>An early positive component of the visual evoked potential</td>
</tr>
<tr>
<td>Pd</td>
<td>Distractor positivity component of the visual evoked potential</td>
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<tr>
<td>PET</td>
<td>Positron emission tomography</td>
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<tr>
<td>PRP</td>
<td>Psychological refractory period</td>
</tr>
<tr>
<td>Ptc</td>
<td>Temporal contralateral positivity</td>
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<tr>
<td>RGB</td>
<td>Red-green-blue colour coordinates</td>
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<tr>
<td>RSVP</td>
<td>Rapid serial visual presentation</td>
</tr>
<tr>
<td>RT</td>
<td>Reaction time</td>
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<tr>
<td>SD</td>
<td>Standard deviation</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>SE</td>
<td>Standard error</td>
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<tr>
<td>SOA</td>
<td>Stimulus onset asynchrony</td>
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<td>SMG</td>
<td>Supramarginal gyrus</td>
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<tr>
<td>SSVEP</td>
<td>Steady-state visual evoked potential</td>
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<tr>
<td>STM</td>
<td>Short-term memory</td>
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<tr>
<td>TC</td>
<td>Target-coloured</td>
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<tr>
<td>tDCS</td>
<td>Transcranial direct current stimulation</td>
</tr>
<tr>
<td>TEO</td>
<td>Temporal occipital cortex</td>
</tr>
<tr>
<td>TMS</td>
<td>Transcranial magnetic stimulation</td>
</tr>
<tr>
<td>TPJ</td>
<td>Temporoparietal junction</td>
</tr>
<tr>
<td>V1</td>
<td>Primary visual cortex</td>
</tr>
<tr>
<td>V2</td>
<td>Visual area 2</td>
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<tr>
<td>V3</td>
<td>Visual area 3</td>
</tr>
<tr>
<td>V4</td>
<td>Visual area 4</td>
</tr>
<tr>
<td>VFC</td>
<td>Ventral frontal cortex</td>
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<tr>
<td>VSTM</td>
<td>Visual short-term memory</td>
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<tr>
<td>WCST</td>
<td>Wisconsin card sort task</td>
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<tr>
<td>WM</td>
<td>Working memory</td>
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<tr>
<td>O-Span</td>
<td>Operation span task</td>
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</table>
Chapter 1. General introduction
1.1. Overview

To avoid being overloaded by the vast amount of information entering the eyes, the human brain has developed various mechanisms for quickly and efficiently identifying information that is likely to be behaviourally relevant, and sifting out everything likely to be irrelevant\(^1\). Part of this sifting involves the physical construction of the eyes. Due to the distribution of photoreceptors in the human retina, visual acuity and colour sensitivity are high within a central region of the visual field, called the fovea, and drop off dramatically in the visual periphery (Green, 1970). As a consequence, when reading this paragraph it is only possible to accurately identify a couple of words at a time, before having to shift one’s gaze to bring the next phrase onto the fovea. This gaze shifting represents one example of a set of cognitive mechanisms aimed at identifying behaviourally relevant sensory information, collectively referred to as **selective attention** (Evans et al., 2011). The technical name for gaze shifting is overt voluntary spatial attention. The term *overt* refers to the fact that the fovea is physically moved to an item being attended, or selected for further processing (Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). The opposite of this, *covert* attention, refers to situations in which something is attended without any movement of the eyes (Ericksen & Hoffman, 1972; Posner, 1980). For example, it is possible within certain limits to keep the eyes fixed on one word and attend covertly to the words that follow it one at a time. The term *voluntary* suggests conscious and intentional selection of what will be attended. The opposite of this, *involuntary* attention, refers to situations in which attention is captured by something in the external environment (Rauschenberger, 2003). An example would be if someone entering your office compelled you to look up from your reading\(^2\). The term *spatial* indicates that attention is directed to a specific location in the visual field. Attention can also be directed to a specific object (Duncan, 1984), or to a specific physical feature such as the colour red (Treisman & Gelade, 1980), which might come in handy when locating a red pen when unsure of its precise location. This last mode of *feature-based* attention constitutes the first of the three main foci of my thesis.

A second main focus of my thesis is how – and in fact whether – the boundary between voluntary and involuntary attention can be clearly defined. Several previous theories have proposed that involuntary attentional capture occurs rapidly and very early in the course of perceptual processing, whereas the voluntary control of attention occurs more slowly and only influences later stages of perception.

\(^{1}\) These mechanisms exist for all of our sensory modalities (Roper & Vecera, 2012), but both my PhD research and the present literature review are restricted to the visual modality.

\(^{2}\) The distinction between voluntary and involuntary attention has also been referred to by various researchers as endogenous versus exogenous, top-down versus bottom-up, and goal-driven versus stimulus-driven attention.
processing (e.g., Cave & Wolfe, 1990; Theeuwes, 1992; Treisman & Sato, 1990). It is increasingly apparent, however, that voluntary and involuntary control of attention are not as distinct as these theories would suggest (Awh, Belopolsky, & Theeuwes, 2012; Gilbert & Li, 2013). As discussed in Section 1.2, attentional capture and early stages of perception appear to be influenced not only by attributes of an observer’s external environment (Wolfe & Horowitz, 2004), but also by goal-related factors such as the stimulus features relevant to their current task (Folk et al., 1992). The ability to bias attentional capture and early sensory processing toward task-relevant stimulus features appears to depend on a network of executive control regions in frontal and parietal cortices (Corbetta, Patel, & Shulman, 2008; Evans et al., 2011).

The third main focus of my thesis is how feature-based attention relates to other executive control functions. The frontal and parietal executive control network involved in feature-based attention, and indeed selective attention more generally, is also thought to be involved in a range of other executive control functions. These include working memory (WM), or the temporary storage and manipulation of information selected from current events and previous experiences (Baddeley, 2012). In Section 1.3 I give a brief introduction to the concept of WM and some of the previous research into it. In Section 1.4 I go on to describe previous research suggesting links between various aspects of selective attention and various aspects of WM (e.g., Awh, Vogel, & Oh, 2006; Gazzaley & Nobre, 2012; Lavie et al., 2004). One link that has not yet been extensively explored in this previous research is the relationship between WM and feature-based attention. Testing for such a link has been the one of the main goals of my empirical research.

1.2. Attentional capture and feature-based attention

1.2.1. Behavioural studies of attentional capture and feature-based attention

Posner (1980) conducted important early research into involuntary attentional capture, using what is now commonly referred to as the ‘Posner’ or ‘spatial cueing’ paradigm. In this paradigm observers keep their eyes fixed on a central point surrounded by two or more placeholders. Their task is to detect or identify a target item that appears in one of the placeholders. Just before the target item appears a spatial cue, such as a luminance change in one of the placeholders, is presented at the same location as the subsequently presented target (a valid cue) or at a different location (an invalid cue). The dependent measure is typically a cue validity effect; the extent to which reaction times (RTs) are faster in the valid relative to invalid cue condition. This RT difference is typically interpreted as a measure of the extent to which spatial attention shifts to the cue’s location. Posner (1980) found a reliable cue validity effect when the cue was predictive of the target location,
suggesting that participants were voluntarily using the cue to guide behaviour. Interestingly, there was still a cue validity effect when the cue was non-predictive, in which case the participants should have had no reason for voluntarily deploying attention to the cued location. Most compellingly, when the target was less likely to appear at the cued location than other locations (counter-predictive), there was still a cue validity effect at very short cue-target stimulus onset asynchronies (SOAs), even though shifting attention to the cued location in this case would have hindered task performance. It was only at longer SOAs (more than 200 ms) that this effect switched direction, such that participants responded more quickly in the uncued (but statistically more likely) location. Posner interpreted these findings as evidence that (1) under some conditions spatial attention can be captured involuntarily, and (2) voluntary and involuntary attention are distinct processes that take place over different time-scales and may involve different pools of neural resources (see also Koshino, Warner, & Juola, 1992; Theeuwes, 1990; Yantis & Jonides, 1984).

Following on from Posner’s early demonstrations a number of studies indicated that the extent of involuntary attentional capture is influenced by the physical properties of the attention-grabbing stimulus. Jonides and Yantis (1988) had participants search through letter arrays for the presence of a specific target letter. One of the letters was a feature singleton, meaning that it differed from all others on a particular feature dimension. The singleton letter was uninformative in that it was just as likely to be the target letter as any other letter. Jonides and Yantis measured the extent to which the singleton letter captured attention away from the target letter as an RT difference between when the singleton was the target letter and when the singleton was a different letter. They compared this RT difference between three types of singletons: a colour singleton, which was a red letter amongst white letters; an intensity singleton, which was a high luminance letter amongst lower luminance letters; and an onset singleton, which was presented in a previously unoccupied visual field location whereas all other letters were revealed by removing some of the parts of a square-sided figure eight. Target RTs were influenced by the validity of the onset singleton, but not of the colour or intensity singleton. The authors interpreted this as evidence that not all stimuli capture attention to the same extent, and in particular, that stimuli that onset suddenly capture attention more readily than other stimuli (see also Theeuwes, 1991b).

In a series of studies, Theeuwes (1991a, 1992, 1994a, 1996) found evidence that attentional capture might also be inherently biased toward other physical stimulus attributes. These studies employed an additional singleton paradigm, an example of which is depicted in Figure 1-1. In this example, observers had to identify the orientation (horizontal or vertical) of a target bar located in a search array. The target was defined as the bar that appeared within a placeholder that was a singleton on
one of two dimensions: form, for example a circle amongst diamonds; or colour, for example a red placeholder amongst green placeholders. Occasionally one of the other placeholders was a singleton on the other, currently task-irrelevant, dimension. Observers were instructed to ignore this additional singleton, which served as a distractor and was intended to capture attention away from the target item. The extent to which target RTs were longer in the presence (versus absence) of the additional singleton was taken as a measure of the extent to which the additional singleton captured attention to its location. Theeuwes (1991a; 1992) found that additional colour singletons slowed RTs when observers were looking for form-defined targets, but additional form singletons did not influence RTs when observers were looking for colour-defined targets. Theeuwes interpreted this further evidence that the extent to which a stimulus captures attention is influenced by its physical salience, reasoning that colour singletons are more physically salient than form singletons (see also Joseph & Optican, 1996; Remington, Johnston, & Yantis, 1992). Based on findings such as these, Theeuwes proposed the *stimulus-driven capture* hypothesis, which states that certain salient stimuli will always capture attention, irrespective of an observer’s current task or goals.

![Diagram](image)

Figure 1-1 Additional singleton paradigm used by Theeuwes (1991a). Participants reported the orientation (horizontal or vertical) of the bar within a target singleton defined by either form or colour. An additional task-irrelevant singleton on the other dimension was also present on half of the trials. This figure was modified from Theeuwes (1991a).

Further support for the stimulus-driven capture hypothesis was later provided by measurements of involuntary shifts in eye position toward task-irrelevant stimuli, also referred to as ‘oculomotor capture’. Theeuwes, Kramer, Hahn, and Irwin (1998) had observers saccade to and then identify a letter located within a colour singleton placeholder. On half of the trials all items were revealed by removing parts of forward masks such that there was no onset associated with them. (The forward masks consisted of digital-clock style figure eights, arms of which could be removed to leave behind any of the possible letter stimuli.) On the other half of trials, an additional onset singleton
appeared in a previously unoccupied visual field location. Even though observers knew that the target would not onset suddenly and would not appear at a previously unoccupied location, their eyes often first moved toward the additional onset singleton before being redirected toward the target item (see also Irwin, Colcombe, Kramer, & Hahn, 2000; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999). These findings were interpreted as further evidence that salient stimuli such as onsets will capture attention even if they are known to be task-irrelevant.

Folk et al. (1992) noted that in many early studies of attentional capture (e.g., Theeuwes, 1991a) it was not only distractors but also target items that were characterised by sudden onset. They set out to systematically investigate the influence of what an observer is looking for – their “task set” – on attentional capture. They modified the Posner cueing paradigm such that both cues and targets could be defined either by colour (red object amongst 3 white distractor objects) or by onset (the only new objects to appear, in white; see Figure 1-2). When observers were looking for red target items, red cues elicited a standard cue validity effect, but onset cues did not. In contrast, when observers were looking for onset targets, onset cues elicited a cue validity effect, but colour cues did not (see also Folk & Annett, 1994; Folk & Remington, 1999; Gibson & Kelsey, 1998; Remington, Folk, & McLean, 2001). Follow-up studies demonstrated the same pattern of results when comparing between cues and targets defined on the same feature dimension but with different feature values (e.g., green cues influenced RTs when observers were looking for green - but not red - targets; Folk & Remington, 1998). To explain their findings, Folk et al. (1992) proposed the contingent capture hypothesis, according to which involuntary attention shifts are contingent on task demands. Specifically, when an observer is engaged in a specific task, attentional capture will be biased toward stimuli that possess features relevant to that task.

A number of earlier theories had also proposed that attention can be guided by object features, independent of spatial attention (e.g., Bundesen, 1990; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Koch & Ullman, 1985; Neisser, 1967; Treisman & Gelade, 1980).
A strict version of the contingent capture hypothesis predicts that distracting stimuli only capture attention when they possess some attribute relevant to an observer’s current task set. Theeuwes’s (1991a; 1992) finding that the presence of colour singletons slowed target RTs when observers were looking for form targets appears to contradict the strict version of the contingent capture hypothesis, although Bacon and Egeth (1994) put forward an alternative interpretation. They argued that in these studies participants might have adopted a singleton detection mode rather than a feature search mode; that is, searching for any singleton items rather than for an item specifically possessing the target-defining feature (see also Bravo & Nakayama, 1992; LaBerge & Brown, 1989). Bacon and Egeth supported this argument using a modified version of Theeuwes’s (1992) additional singleton paradigm. They set out to discourage participants from employing a singleton detection mode by changing the stimuli such that the form target (a circle) was no longer always a shape singleton. They achieved this either by presenting multiple target circles on some trials (Experiment 2), or by introducing heterogeneity into the distractor shape arrays (such that these items could be triangles and squares as well as diamonds; Experiment 3). In both of these experiments, there was no longer any influence of additional colour singletons on form target RTs (but see Theeuwes, 2004). These findings suggest that the search strategy observers employ can modify the interference produced by physically salient distractors, which further supports the notion that task-related factors can influence attentional capture.
Wu and Remington (2003) provided further evidence that attentional capture by task-irrelevant singletons is reduced when a singleton detection mode is discouraged, using measurements of oculomotor capture. They used a paradigm very similar to the previously described oculomotor capture study by Theeuwes et al. (1998), in which an additional onset singleton was presented during search for an item defined by a particular colour. They found that, although onset singletons attracted a substantial number of eye movements when the colour target was a singleton, introducing heterogeneity into the non-target colours (such that the target was no longer a colour singleton) dramatically reduced the number of eye movements toward the onset singleton. The notion that observers’ search strategies influence whether salient stimuli capture attention has been supported by several other studies, using a variety of paradigms and measures of capture (Folk & Anderson, 2010; Gibson & Kelsey, 1998; Theeuwes & Burger, 1998; Todd & Kramer, 1994; Yantis & Egeth, 1999).

In addition to questions about how observers’ search strategies may influence results, various other challenges have been raised about the interpretation of the behavioural findings discussed so far (for discussions, see Folk & Remington, 2006, 2010; Leber & Egeth, 2006; Lien, Ruthruff, & Johnston, 2010; Theeuwes, 2010; Theeuwes, Atchley, & Kramer, 2000; Yantis, 2000). At the heart of most of these challenges has been the notion that rather than providing a direct index of involuntary attentional capture, behavioural responses reflect the end-point in a set of perceptual, decisional, and response processes. As such, effects on behavioural measures such as RT and error rate are invariably open to multiple alternative explanations, as they could reflect changes in any of a number of different processing stages. Such criticisms have been levelled both at studies used as evidence for stimulus-driven capture, and also at studies used as evidence for contingent capture. In the following paragraphs, I outline some of the alternative explanations put forward for behavioural findings used as evidence for each hypothesis. I then move on to discuss research using a variety of other measurement techniques that are arguably less susceptible to some of these alternative explanations, and have provided new avenues for investigating the various influences on attentional capture.

In terms of evidence for stimulus-driven capture, Folk and Remington (1998) argued that Theeuwes’s (1991a; 1992) findings of slower RTs in the presence of an additional irrelevant singleton could result from the capture of spatial attention to the singleton location, but could also result from a non-spatial filtering cost (Kahneman, Treisman, & Burkell, 1983; Treisman, Kahneman, & Burkell, 1983) associated with the irrelevant singleton delaying the deployment of attention to the target item. To attempt to distinguish between these two possibilities, Theeuwes
(1996) modified the additional singleton paradigm such that the item within the additional singleton could either be congruent or incongruent with the target item (i.e., could either have the same identity or a different identity; also referred to as compatible versus incompatible). Theeuwes (1996) found that target RTs during a form search were influenced not only by the mere presence of a colour singleton, but also by the congruency of the item within the colour singleton (see also Theeuwes & Burger, 1998; Theeuwes & Van der Burg, 2011). Theeuwes argued that these findings represented further evidence that spatial attention shifted to the location of the additional singleton. Folk and Remington (1998) rejected this argument, however, stating that even congruency effects do not necessarily mean that spatial attention shifted to the location of the additional singleton. They argued that processing of the item within the additional singleton could have been facilitated even though spatial attention was focused on a different location. Theeuwes and Godijn (2002) later countered this rebuttal using the phenomenon of inhibition of return (IOR; Klein, 2000; Posner & Cohen, 1984), whereby the facilitation of responses to targets presented at spatially attended locations is followed by a period in which targets subsequently presented at that location are responded to more slowly. Theeuwes and Godijn found evidence for IOR at the location of additional singletons. They used this as further support for the argument that adequately salient additional singletons can indeed capture spatial attention to their location, as opposed to only inducing non-spatial filtering costs (see also Theeuwes & Chen, 2005).

There have also been challenges to the interpretation of behavioural findings initially used as evidence for contingent capture (e.g., Folk et al., 1992). For example, using a rapid serial visual presentation (RSVP) paradigm, Ghorashi, Zuvic, Visser, and Di Lollo (2003) found that distractors presented up to 600 ms before a target item slowed target responses more if they possessed the target-defining feature, regardless of whether the distractors appeared at a different location than the target or at the same location. The authors argued that these findings suggest that the differences in interference produced by task-relevant (versus task-irrelevant) distractors must reflect – at least in part – different processing stages independent of spatial attention (see also Visser, Bischof, & Di Lollo, 2004).

Theeuwes et al. (2000; see also Theeuwes, 1994a, 1994b) also questioned whether the influence of task-relevance on cue validity effects can be conclusively attributed to effects at the level of spatial attentional capture. He argued that differences in cue validity effects as a function of task-relevance could reflect differences in the speed at which spatial attention can be disengaged from the cues, rather than differences in the extent to which the cues capture spatial attention. According to this rapid disengagement hypothesis, all salient stimuli involuntarily capture attentional resources, but
voluntary control settings then act to rapidly disengage these resources from stimuli easily identified as irrelevant to the current task. Earlier theoretical accounts had also argued that stimulus-based and task-based factors influence attentional capture at distinct stages, with stimulus characteristics influencing early “preattentive” processing stages and task set only influencing later stages of processing (e.g., Cave & Wolfe, 1990; Treisman & Gelade, 1980; Treisman & Sato, 1990; Treisman & Souther, 1985; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). Theeuwes et al. (2000) suggested that in spatial cueing studies attention is always captured by the cue to an extent defined solely by the cue’s physical salience, irrespective of the observer’s task set. They suggested, however, that the speed at which attention can be disengaged from the cue is dependent on the observer’s task set, such that it takes longer to disengage from cues with task-relevant features. To test their rapid disengagement hypothesis, Theeuwes et al. modified the additional singleton paradigm by introducing a variable SOA between the additional singleton and the rest of the search array. The additional singletons slowed target RTs if presented at the same time as the rest of the search array, replicating Theeuwes’s earlier studies. In contrast, the additional singletons did not influence target RTs if they onset 150 ms or more prior to the rest of the search array (see also M. S. Kim & Cave, 1999; Lamy & Egeth, 2003). Theeuwes et al. suggested this was because presenting the additional singletons prior to the rest of the search array allowed time for the observers to disengage their attention from them before the target appeared.

Proponents of the contingent capture hypothesis put forward alternative explanations for the findings used to support the rapid disengagement hypothesis. Folk and Remington (2006) pointed out that Theeuwes et al.’s (2000) observation that additional singletons no longer influenced target RTs when presented 150 ms or more before the rest of the search array could have been due to participants having more time to disengage spatial attention from the additional singleton, but could also have been due to participants having more time to overcome non-spatial filtering costs associated with the additional singleton. Folk and Remington (2006) then went on to demonstrate that both congruency effects and IOR are also evident in a spatial cueing paradigm, but only for cues that possess the current target colour. They argued that these observations further supported the contingent capture hypothesis that only task-relevant stimuli capture spatial attention. Chen and Mordkoff (2007) raised a further challenge for the rapid disengagement hypothesis. Using a paradigm almost identical to that used by Folk et al. (1992), they demonstrated that onset cues still failed to evoke a cue validity effect during a colour search even when the cue-target SOA was reduced from 150 ms down to 35 ms. Other studies have also found effects of task set on cue validity effects at very short cue-target SOAs (Folk & Remington, 1998; Lamy, 2005). Given these findings, if the rapid disengagement hypothesis is correct, it is possible to shift attention to the
location of a salient onset cue, identify it as task-irrelevant, and then disengage attention, all in less than 35 ms. Although technically possible, this is perhaps unlikely given the number of synaptic connections likely to be involved in this series of processes.

Many researchers have attempted to avoid the various alternative explanations that have been put forward for the behavioural results described thus far by using other, non-behavioural measures of attentional capture. Cognitive neuroscientists have access to a variety of tools for measuring the processing of sensory events that are independent of the observer’s response. These include electroencephalography (EEG; Luck, 2005), invasive electrophysiological recordings (Peelen & Kastner, 2014), functional magnetic resonance imaging (fMRI; Huettel, Song, & McCarthy, 2004), and transcranial magnetic stimulation (TMS; Pascual-Leone, Davey, Rothwell, Wasserman, & Puri, 2002). Although each of these tools has its own limitations, each also has its own unique strengths, and together they afford a unique perspective on the neural mechanisms underlying cognitive processes. Moreover, integrating observations across all of the measurement tools available – both behavioural and neurophysiological – can give a clearer and deeper understanding than can be provided by any one measurement tool considered in isolation. In the following sections, I give an overview of the neurophysiological research that has investigated feature-based attention and attentional capture.

1.2.2. Electrophysiological studies of attentional capture and feature-based attention

The high temporal resolution of EEG makes it well suited to addressing the question of how early in the time course of perceptual processing feature-based attention can have its effects. One EEG-based measure that has been applied to this question is the N2 posterior contralateral component of the visual evoked response (N2pc; Luck, 2012; Luck & Hillyard, 1994b; see Figure 1-3 for an illustration). The N2pc is generally accepted as an index of the covert allocation of visual resources toward a lateralised visual field location (Eimer & Kiss, 2010a; Woodman & Luck, 2003; but see Theeuwes, 2010). Unlike behavioural measures of attentional capture, early electrophysiological measures such as the N2pc are likely to predominantly reflect perceptual processes, uncontaminated by later decisional and response processes. Hickey, McDonald, and Theeuwes (2006) set out to test the strict version of the contingent capture hypothesis, which argues that distractors only capture attention when they possess a task-relevant feature, by measuring the N2pc associated with salient but task-irrelevant singletons in Theeuwes’s (1992) additional singleton paradigm (see Figure 1-3). They found that colour singletons presented while observers were searching for a form singleton evoked a small but reliable N2pc, and interpreted this as evidence that spatial attention can indeed
be captured by completely task-irrelevant stimuli. As Eimer and Kiss (2010b) point out, however, Bacon and Egeth’s (1984) argument that these singletons may actually have been task-relevant if participants were adopting a singleton detection mode of search applies to these results too. Eimer and Kiss (2010b) supported this argument by demonstrating a reduced N2pc associated with task-irrelevant distractors when task instructions were manipulated to discourage a singleton detection mode (see also Eimer, Kiss, & Nicholas, 2011; Lien, Ruthruff, & Cornett, 2010).

Figure 1-3 Illustration of the N2pc component, using the study by Hickey et al. (2006) as an example. (a) EEG data were recorded while observers searched for a form singleton (a diamond amongst circles). Occasionally an additional colour singleton (a green circle) was also present within the search array. Note that when both singletons were present, one was presented on the horizontal midline so that any lateralised activity in the EEG data could be solely attributed to the other, lateralised, singleton. (b) Event-related potential (ERP) waveforms associated with the additional colour singleton at electrodes PO7 and PO8. The data are displayed separately for the electrode contralateral to the colour singleton location (e.g., PO8 when the colour singleton was in the left visual hemifield; the green line in Panel b) and ipsilateral to the colour singleton location (e.g., PO7 when the colour singleton was in the left visual hemifield; the red line in Panel b). The N2pc associated with the additional singleton, indicated by the dashed lines in Panel b, is a greater negativity in the contralateral relative to the ipsilateral waveform roughly 200 – 300 ms after stimulus onset. Note that negative is plotted upwards. This figure was modified from Hickey et al. (2006).

Numerous other studies of the N2pc have found evidence for a less strict version of the contingent capture hypothesis, namely that the extent to which distractors capture attention is influenced by the extent to which they possess features relevant to an observer’s task. For example, Lien, Ruthruff, Goodin, and Remington (2008) had observers search for a target letter of a certain colour within an array preceded by multiple spatial cues defined either by the target colour, a different colour, or an onset. Target-coloured cues elicited a cue validity effect on target RTs, but the other cue types did not, consistent with previous behavioural findings (e.g., Folk et al., 1992). Additionally, target-
coloured cues evoked an N2pc, suggesting they had captured attention to their location even when presented in the opposite visual field to one of the other cue types. This effect was observed despite the target-coloured cue being presented simultaneously with either a competing cue of a different colour, or with a competing onset cue. Many other studies have similarly found that when distractors possess the same feature value that defines a searched-for target, they evoke a reliable N2pc, but when targets are defined by a different feature value the same distractors evoke an N2pc of significantly reduced amplitude, or even no N2pc at all. This pattern of results has been observed using a variety of target-defining feature dimensions (including colour, orientation, size, and motion direction), and in the context of spatial cueing paradigms (Eimer & Kiss, 2008; Eimer, Kiss, Press, & Sauter, 2009; Lien, Ruthruff, & Cornett, 2010), additional singleton paradigms (Kiss, Jolicœur, Dell'acqua, & Eimer, 2008), other visual search paradigms (Girelli & Luck, 1997; Rodríguez Holguín, Doallo, Vizoso, & Cadaveira, 2009), and RSVP paradigms (Leblanc, Prime, & Jolicœur, 2008). Overall, these studies indicate that an observer’s feature-based search settings can modulate not only behavioural but also electrophysiological indices of attentional capture.

Sawaki and Luck (2013) also examined the influence of feature-based attention on a second contralateral component, referred to as the Pd (distractor positivity; Hickey, Di Lollo, & McDonald, 2009) component. The Pd is similar to the N2pc in that it is evoked at posterior electrodes contralateral to lateralised visual stimuli, but different in that (1) it has an opposite polarity (being positive rather than negative at contralateral posterior electrode locations), and (2) it appears to be consistently evoked not only by targets, but also by distractors – even if the distractors do not evoke an N2pc (Sawaki, Geng, & Luck, 2012). Such observations have led previous researchers to infer that the Pd component reflects the active suppression of attentional capture, rather than attentional capture itself (e.g., Sawaki & Luck, 2010). Noting that the Pd tends to appear subsequent to the N2pc when both components are evoked by the same stimulus, Sawaki et al. (2012) suggested that the Pd may also reflect the termination of attentional capture once perceptual analysis is complete. Sawaki and Luck (2013) had observers identify a target item of a specific colour in a spatial cueing paradigm. Both the cue array and the target array consisted of four differently coloured items. Behaviourally, RTs to the target item were faster when it appeared at the location of the target-

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4 It may be tempting to take observations that distractors do not evoke a reliable N2pc when they do not possess any task-relevant features as evidence for the strict version of the contingent capture hypothesis. Such an interpretation assumes that the absence of a reliable N2pc is a definitive indication that no attentional capture occurred. I argue that direct support for such an assumption is not available.

5 This might be the same component as the Ptc (temporal contralateral positivity) component described in other studies (e.g., Hilimire, Mounts, Parks, & Corballis, 2009, 2010, 2011).
coloured cue relative to one of the other three locations, in line with previous behavioural evidence for contingent capture (e.g., Folk et al., 1992). Additionally, Sawaki and Luck (2013) observed both an N2pc and a subsequent Pd contralateral to the location of the target-coloured cue. Because this item only differed from the other concurrently presented cue items in terms of whether it possessed a task-relevant feature, these findings suggest that feature-based attention can influence both attentional capture by distractor items, and also active suppression of attentional capture by those items. Some degree of caution must be taken when considering this interpretation, however, because the N2pc and Pd components occur in close temporal proximity at the same electrodes. Therefore, one cannot rule out the possibility that an apparent effect on one of these components may actually reflect an effect in the opposite direction on the other.

In addition to these contralateral, attention-related components, there have also been a number of demonstrations that feature-based task settings can influence “standard” early visual ERP components that are associated with all visual stimuli. Within the current focus of spatial attention, having observers monitor for items with a specific feature increases the amplitude of early visual ERPs evoked by stimuli with that feature as early as 100 ms after they appear. Such findings have been demonstrated for tasks involving attention to a specific colour (Hillyard & Münte, 1984; Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004), motion direction (Hillyard & Anllo-Vento, 1998), and line orientation (Akyürek & Schubö, 2013). W. W. Zhang and Luck (2009) extended on these findings by demonstrating an influence of feature-based attention on early visual ERPs associated with stimuli presented outside the focus of spatial attention. They had observers monitor dot fields of a particular colour in one location while recording early visual ERPs associated with probe dot fields of either that same or a different colour in a different, ignored, location. Relative to non-target-coloured probes, target-coloured probes evoked a larger P1, an early visual ERP component beginning less than 100 ms after stimulus onset which Zhang and Luck suggest might reflect the initial feedforward sweep of activity through visual cortex (see also Moher, Lakshmanan, Egeth, & Ewen, 2014; note, however, that these studies and their findings will be discussed in greater detail in Chapter 4). Early effects of feature-based attention outside the current locus of spatial attention have also been found for motion direction (Stoppel et al., 2012) and line orientation (Bondarenko et al., 2012).

Other researchers have examined the effects of feature-based attention on early visual processing using “frequency tagging” of steady-state visual-evoked potentials (SSVEPs). These are cyclical oscillations in EEG data evoked when an observer is exposed to a visual stimulus that is flickering (e.g., appearing and disappearing) at a fixed frequency. These oscillations are believed to result
from temporal entrainment of responses to the visual stimulus in early visual cortex (Di Russo et al., 2007; Toffanin, de Jong, Johnson, & Martens, 2009; Vialatte, Maurice, Dauwels, & Cichocki, 2010). The magnitude of these SSVEP oscillations can be used as an index of the strength of the neural representation of the flickering object in early visual cortex. Muller et al. (2006) presented observers with overlapping fields of moving red and blue dots, with each colour flickering at a different frequency. Their task was to monitor either the red or the blue dots for occasional brief periods of coherent motion. The dots were small enough and moving quickly enough that observers could not perform the task by simply focusing spatial attention on any single dot, forcing them into a feature-based attentional strategy. The magnitude of the SSVEP response was significantly larger for dots with the attended- relative to ignored- feature value (see also Andersen, Fuchs, & Müller, 2011; Andersen, Hillyard, & Müller, 2008; Andersen & Müller, 2010; Bridwell & Srinivasan, 2012; Garcia, Srinivasan, & Serences, 2013). These findings further support the notion that attending to objects with a specific feature can modulate early stages of sensory processing.

Painter, Dux, Travis, and Mattingley (2014) used SSVEPs to investigate whether feature-based attention effects on sensory processing involve the enhancement of task-relevant features, or the suppression of task-irrelevant features. They had observers monitor for letters defined by a specific conjunction of colour and identity features (e.g., an upright red T) within arrays of letters with different colours and identities (e.g., red and green Ts and Ls), and measured SSVEPs associated with distractor objects flickered in the periphery. The distractor objects could be either the target colour, the other colour present in the letter array, or a third colour used as a baseline. Relative to the SSVEPs associated with the baseline-coloured distractors, there was an enhancement of SSVEPs associated with the target-coloured distractors, but no change in those associated with non-target coloured distractors (but see Andersen & Müller, 2010). These findings suggest that feature-based attention is primarily driven by the selective enhancement of responses to objects possessing task-relevant features. This possibility is also supported by psychophysical evidence that feature-based attention enhances sensitivity to task-relevant features, rather than reducing sensitivity to task-irrelevant features (see White & Carrasco, 2011).

Further evidence that feature-based attention affects early neural responses in hierarchically early regions of sensory cortex has been provided by invasive electrophysiological recording studies in monkeys. Bichot, Rossi, and Desimone (2005) recorded from neurons in colour- and shape-sensitive visual area V4 while monkeys made a series of saccades through a static array of coloured shapes, searching for a target object of a specific colour and shape. As the monkeys searched through the array, V4 neurons that preferred the current target features increased their firing rates
whenever an object with at least one of the target-defining features (e.g., a green circle when they were looking for a green diamond) fell within their receptive fields. This effect was apparent irrespective of whether the object went on to be selected as the next saccade target. This feature-based increase in firing rate began very shortly after an object moved into a neuron’s receptive field; around 50 ms for preferred colour matches, and 150 ms for preferred shape matches. Numerous other non-human primate studies have also demonstrated early effects of feature-based attention on activity in V4 (David, Hayden, Mazer, & Gallant, 2008; Hayden & Gallant, 2009; McAdams & Maunsell, 2000; Motter, 1994a, 1994b) and also in other feature-selective areas of visual cortex, such as motion-sensitive area MT (Treue & Martinez Trujillo, 1999).

Modern theories of attention (e.g., Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Haenny & Schiller, 1988) generally propose that such attentional control of processing in early sensory cortices is implemented by “executive control” regions in prefrontal and parietal cortices (for details, see Boynton, 2005; Corbetta et al., 2008; Desimone, 1998; Evans et al., 2011; Kastner & Ungerleider, 2000; Noudoost, Chang, Steinmetz, & Moore, 2010; Yantis, 2000). One example is Desimone and Duncan’s (1995) biased competition model. As illustrated in Figure 1-4, this model proposes that information is passed from primary visual cortex up through two distinct streams; a dorsal stream that travels through the parietal cortex and is primarily involved in processing spatial information, and a ventral stream that travels through temporal cortex and is primarily involved in object recognition (see also Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Haxby, 1994). Both streams relay information to the prefrontal cortex and, importantly, feedback signals are also communicated along both streams6. One proposed role of these feedback signals is to bias processing toward task-relevant objects and locations.

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6 In contrast, earlier theories (e.g., D. E. Broadbent, 1958; Hubel & Wiesel, 1962, 1968; Marr, 1982; Treisman, 1969) tended to conceptualise perception as a primarily or exclusively feedforward process, with information being passed from primary visual cortex (V1) up through a hierarchy of visual areas that responded to progressively larger and more complex stimuli (Boussaoud, Desimone, & Ungerleider, 1991). Early evidence against these theories came from anatomical studies indicating that in addition to the axons projecting from lower- to higher-level brain regions within the visual system, there are a comparable number of axons projecting from higher- to lower-level brain regions, and also within and between brain regions at the same level of the hierarchy (Borra et al., 2008; Felleman & Van Essen, 1991; Schall, Morel, King, & Bullier, 1995).
Although EEG has been a very useful tool for investigating the time-course of feature-based influences on attentional capture, its low spatial resolution limits its usefulness in testing hypotheses about the network of brain regions involved in generating feature-based attention. Such an endeavour is, however, well suited to more spatially precise techniques such as MRI, neurostimulation, and lesion studies. In the following sections, I review evidence from these techniques that the effects of feature-based attention on early visual areas are implemented by feedback signals from executive control regions within frontal and parietal cortices.

1.2.3. Neuroimaging studies of attentional capture and feature-based attention

Serences et al. (2005) set out to identify the brain networks involved in feature-based attention using fMRI. They had observers monitor a serially presented stream of coloured letters at fixation for target letters of a particular colour. Two additional irrelevant streams of letters were presented to the left and right of fixation. These peripheral letter streams were mostly coloured grey, but occasionally briefly changed to either the target colour or a different colour. Behaviourally, the presence of target-coloured distractors in the peripheral letter streams slowed responses to target letters, but the presence of non-target-coloured distractors did not, in line with previous behavioural
results (e.g., Folk et al., 1992). Additionally, target-coloured distractor letters evoked a larger blood oxygen-level dependent (BOLD) response in extrastriate visual cortex, and also in a network of frontal and parietal brain regions including the frontal eye fields (FEF), intraparietal sulcus (IPS), temporoparietal junction (TPJ), and ventral frontal cortex (VFC). Numerous other studies have also found activation of this network of frontal and parietal brain regions during feature-based attention tasks (Egner et al., 2008; Giesbrecht, Woldorff, Song, & Mangun, 2003; Greenberg, Esterman, Wilson, Serences, & Yantis, 2010; Jehee, Brady, & Tong, 2011; Liu, Larsson, & Carrasco, 2007; Luks & Simpson, 2004; Reeck, Labar, & Egner, 2012; Saenz, Buracas, & Boynton, 2002, 2003; Serences & Yantis, 2007; Shulman et al., 1999; Slagter et al., 2007; Vandenberghe, Gitelman, Parrish, & Mesulam, 2001). Similar regions of frontal and parietal cortex have also been implicated in both voluntary and involuntary spatial attention (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta, Kincade, & Shulman, 2002; Corbetta et al., 2005; De Fockert, Rees, Frith, & Lavie, 2004; Hopfinger, Buonocore, & Mangun, 2000; Lavie & De Fockert, 2006; Melloni, van Leeuwen, Alink, & Muller, 2012; Woldorff et al., 2004). These findings support the notion that feature-based attention (and task settings more generally) influences attentional capture via a highly distributed network of frontal, parietal, and occipital brain regions. Invasive recording studies in non-human primates have provided converging evidence that feature-based attention involves not only early sensory areas but also higher-level regions of cortex in frontal (Zhou & Desimone, 2011) and parietal (Saalmann, Pigarev, & Vidyasagar, 2007) cortices.

Serences and Boynton (2007) provided an important extension to the fMRI studies described above. They had observers monitor a field of dots moving in a specific direction in one location for occasional brief reductions in speed. There were also dots moving in a different direction at the attended location, and occasionally there were also distractor dots moving in both of those directions in the opposite visual field. To discriminate responses to the moving dots as a function of motion direction and location, they used an analysis technique called multi-voxel pattern analysis (MVPA; Haynes & Rees, 2006). This method is more sensitive than traditional methods of analysing fMRI data, and involves evaluating patterns of activity across multiple fMRI voxels at an individual trial level, rather than simply averaging the data together across all trials and considering each voxel in isolation. Serences and Boynton found that the patterns of activity in retinotopically mapped early visual areas (including V1, V2, V3, V4 and MT) differed reliably as a function of the motion direction to which observers were attending. These differences were apparent in both the hemisphere responsive to (i.e., contralateral to) the attended stimuli and also the hemisphere responsive to the ignored distractor stimuli. Patterns of activity in higher-level areas (IPS and FEF) also differed reliably between the two motion attention conditions. Once again, these findings
suggest that attending to a specific feature can modulate stimulus processing throughout the visual 
system and across the visual field (see also Kamitani & Tong, 2005, 2006). Most interestingly, 
patterns of activity in early visual areas in the hemisphere corresponding to the distractor location 
differed depending on which direction observers were attending even when no distractor stimuli 
were present. This suggests that feature-based attention involves pre-emptive changes in activity in 
early visual areas, as opposed to reactive changes that occur only after a stimulus has been 
presented. Similar findings have been observed in the context of spatial attention (Bressler, Tang, 
Sylvester, Shulman, & Corbetta, 2008; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; 
Sylvester, Jack, Corbetta, & Shulman, 2008; Yantis et al., 2002; Yantis & Serences, 2003).

1.2.4. Neurostimulation studies of attentional capture and feature-based attention

Neurostimulation techniques such as TMS provide cognitive neuroscientists with a means of 
investigating the causal role of specific regions of cortex in a task (Merabet, Theoret, & Pascual-
Leone, 2003; Walsh & Cowey, 2000). Using TMS, researchers can very briefly depolarise all 
neurons in a reasonably focal region of cortex at a specific point in time (Hallet, 2007), which is 
presumed to disrupt whatever endogenous activity is occurring at the time (although the precise 
mechanisms of this disruption remain unclear; Miniussi, Ruzzoli, & Walsh, 2010; Rusconi & 
Bestmann, 2009; Siebner, Hartwigsen, Kassuba, & Rothwell, 2009; Ziemann, 2010). It is generally 
reasoned that if applying TMS to a brain region during a cognitive process alters that process, the 
targeted region must be involved (directly or indirectly) in that cognitive process. Schenkluhn, Ruff, 
Heinen, and Chambers (2008) used TMS to investigate the involvement of parietal cortex in 
feature-based attention. They had observers monitor for the presence of a target circle amongst 
rotated Cs in a multi-coloured search array. Prior to each array, participants were either given a cue 
informing them of the location or colour of the upcoming target (both with 100% validity), or were 
given no cue at all. Repetitive trains of TMS pulses were applied in the time interval between the 
cue and the search array, directed toward one of three regions of parietal cortex previously 
implicated in attentional control of visual selection (supramarginal gyrus, SMG; anterior IPS; and 
posterior IPS, all in the right hemisphere). The TMS pulses were intended to disrupt attentional 
control, and their effects were measured in terms of a change in perceptual sensitivity of target 
detection with TMS pulse intensity. TMS to the anterior IPS impaired sensitivity after both spatial 
and featural cues. This finding represents direct causal evidence that the anterior IPS is involved in 
implementing voluntary biases in sensory processing, on the basis of both location-based and 
feature-based attention (see also Du, Chen, & Zhou, 2012; Painter, 2013). TMS to the SMG 
impaired sensitivity after spatial but not featural cues, suggesting that although there are some
common elements in the frontoparietal networks that control spatial and feature-based attention, there are also some divergences (see also Romei, Thut, Mok, Schyns, & Driver, 2012).

1.2.5. Lesion studies of attentional capture and feature-based attention

Studies of patients with lesions arising after brain trauma such as stroke also provide a means of investigating the causal role of specific brain regions in a task. Snow and Mattingley (2006) tested the feature-based attentional capabilities of six patients who had recently suffered a unilateral right hemisphere stroke. All patients showed rightward biases in spatial attentional selection, indicative of damage to the parietal and/or temporal lobes (Driver & Vuilleumier, 2001; Karnath, Ferber & Himmelbach, 2001; Karnath, Himmelbach, & Kuker, 2003; Mort et al., 2003). The patients, and a group of age- and sex-matched healthy controls, were tested in a modified version of the irrelevant flanker paradigm (e.g., Eriksen & Eriksen, 1974), in which responses to a central target item are slower and more error-prone when the target is surrounded by incongruent flanker items. Snow and Mattingley had participants report either the colour (red or green) or identity (letter ‘A’ or letter ‘B’) of a target letter flanked by distractor letters that could either be congruent, incongruent, or neural (e.g., a yellow letter ‘X’) with respect to each target feature dimension. For the healthy controls, target RTs were significantly slowed in the presence of a flanker that was incongruent on the current task-relevant dimension, but not in the presence of a flanker that was only incongruent on the current task-irrelevant dimension. This finding is consistent with other research in healthy individuals (e.g., Maruff, Danckert, Camplin, & Currie, 1999; Remington & Folk, 2001) and the notion that healthy individuals are capable of selectively processing all information on a specific feature dimension, and excluding information on other, currently task-irrelevant feature dimensions (see also Found & Müller, 1996; Töllner, Gramann, Müller, Kiss, & Eimer, 2008). In contrast, for the stroke patients, target RTs were significantly slowed in the presence of a flanker that was incongruent on either the currently task-relevant dimension or on the other feature dimension (see also Danckert, Maruff, Kinsella, de Graaff, & Currie, 1999). This suggests that the parietal brain regions affected in these patients are not only involved in selectively attending to specific spatial locations, but also in selectively attending to specific feature dimensions. Patients with damage to prefrontal cortex have also been found to be impaired on task that require selectively attending to certain information and ignoring salient but task-irrelevant information (for a review, see E. K. Miller & Cohen, 2001). Overall, the neuroimaging, invasive recording, neurostimulation, and lesion studies reviewed above support the notion that the influence of feature-based attention on sensory processing is achieved via feedback connections to early sensory areas from a distributed network of frontal and parietal brain regions (Corbetta & Shulman, 2002; Desimone & Duncan, 1995).
1.3. Links between selective attention and working memory

1.3.1. An overview of working memory

The term “working memory” generally refers to the set of cognitive processes involved in temporarily storing and manipulating information selected from current events and previous experiences (e.g., Baddeley, 2012). Conceptually, WM is quite similar to short-term memory (STM), and the terms have often been used interchangeably. These constructs have long been thought of as fundamentally distinct from long-term memory (LTM), and subserved by distinct brain networks (Atkinson & Shiffrin, 1968; Baddeley, 1976; D. E. Broadbent, 1958). Numerous theoretical models of WM have been put forward over the past half-century (for reviews, see Baddeley, 2012; Jonides et al., 2008; Miyake & Shah, 1999). An early model by G. A. Miller (1956) proposed that sensory information is converted into abstract information chunks (e.g., a digit, a phrase, or an image), which are then held in a central storage buffer. According to this and other early theories (e.g., Atkinson & Shiffrin, 1968; D. E. Broadbent, 1958), the capacity of WM is limited by the amount of information that can be held in this central, ‘amodal’ storage buffer (see also Cowan, 1999, 2001).

In contrast to these early unitary models of WM capacity, Baddeley and Hitch (1974; see also Baddeley, 1983, 1996, 1998, 2003, 2007, 2010, 2012) proposed that WM comprises a set of distinct components. Initially they proposed three components, with the first two involved only in short-term information storage. These components were the visuo-spatial sketchpad for storing visual and spatial information (sometimes referred to as visual short-term memory, VSTM; Phillips, 1974; Phillips & Baddeley, 1971), and the phonological loop for storing auditory and verbal information (Burgess & Hitch, 1992). The third component, the central executive, was proposed to be responsible for a variety of executive control tasks, including: selecting information from sensory input and transferring it to the short-term storage components, which is commonly referred to as

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Note that the phrases “short-term” and “long-term” are somewhat misleading in that there is no precise temporal distinction between these two modes of memory. Note also that recent research has indicated that although there are some differences in the brain networks involved in STM and LTM, there is also a considerable degree of overlap between them (Jeneson & Squire, 2012).
“information-updating”; distributing the allocation of short-term storage space between competing tasks; and switching between tasks\(^8\).

One important aspect of Baddeley and Hitch’s (1974) model is that WM consists of a series of different components, each with access to its own pool of neural resources and independent capacity limit. Support for this assumption has come from studies demonstrating that tasks designed to tax one component interfere with other tasks designed to tax that same component, but have little or no effect on tasks designed to tax other components (for a review, see Baddeley, 1992). For example, holding words or digits in memory impairs the ability to remember a different list of words (Baddeley, Lewis, & Vallar, 1984), but does not impair the ability to remember the colours and locations of a set of visually presented squares (Luck & Vogel, 1997). Since Baddeley and Hitch first proposed their model, evidence has emerged to suggest that some components might be further divisible into sub-components, which are themselves subserved by independent pools of neural resources. In the case of the visuo-spatial sketchpad, neuropsychological dissociations suggest that information about the visual features of objects is stored in different brain regions than information about spatial locations (Baddeley & Logie, 1999; Farah, Hammond, Levine, & Calvanio, 1988; Goldman-Rakic, 1996). Factor analyses of performance on tasks designed to tax the central executive suggest that various functions attributed to it, such as information-updating and task switching, might be at least partly independent from each other (Engle & Kane, 2004; Miyake et al., 2000; Shallice, 2002). These findings suggest that rather than being a unitary finite resource, WM involves multiple independent components.

Another important aspect of Baddeley and Hitch’s (1974) model is the notion that WM involves not only information storage components, but also a central executive for controlling those storage components. Research conducted since Baddeley and Hitch’s model was proposed has indicated that, contrary to the earlier unitary models (e.g., G. A. Miller, 1956), WM capacity limits might be more dependent on the capacity of the central executive than on the capacity of the information storage components. An early and influential indication of this notion was provided by Daneman and Carpenter (1980). Other theorists had previously hypothesised a relationship between WM capacity and reading comprehension, but had not been successful in finding one (Kintsch & van Dijk, 1978; Perfetti & Lesgold, 1977). Daneman and Carpenter speculated this failure was because the previous studies had used measures of WM capacity that only required information storage,\(^8\)

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\(^8\) More recently, Baddeley (2000; see also Baddeley, Allen, & Hitch, 2011) added a fourth component to the model. The episodic buffer, proposed to be involved in binding information from the individual storage components together into integrated “episodes”, can be accessed by conscious awareness and transferred into long-term episodic memory.
without any need to actively manipulate or integrate this information over time. Examples included digit and word span tasks, in which participants were asked to hold a set of digits or words in memory for a fixed amount of time before recalling them verbatim. In their novel reading span measure, Daneman and Carpenter had participants read aloud a series of sentences, presented one at a time. At the end of each sentence, participants had to reproduce from memory a chronological list of the final word of each sentence presented so far. This task requires participants to not only store a progressively longer list of final words in memory, but also to process and reproduce the other words in the sentences and prevent them from taking up storage space once they are no longer required. Unlike the previously used simple information storage measures of WM capacity, the number of final words that each participant could successfully complete correlated highly with three measures of reading comprehension (see also Daneman & Merikle, 1996; Engle, Kane, & Tuholski, 1999). Daneman and Carpenter interpreted this as evidence that individual differences in WM capacity reflect differences in the ability to control and manipulate information in WM, as opposed to differences in how much information can be stored.

A number of other theories have also emphasized the importance of central control processes over storage capacities as limiting factors in WM capacity (Kane, Poole, Tuholski, & Engle, 2006). For example, W. Schneider and Detweiler (1987) proposed that there are a large number of independent storage buffers, but information in the buffers is only available while being kept in an active state by a central controller. The authors suggested that this controller can only keep three or four storage buffers active at any one time, and that this number dictates the capacity of WM. Engle, Kane, et al. (1999; see also Engle & Kane, 2004) argued that WM capacity is largely dependent on the ability to inhibit the processing of unwanted, task-irrelevant information. Engle (2002) even went so far as to suggest that WM and STM are essentially independent constructs, and that the term WM should be reserved for the executive control component of Baddeley and Hitch’s model. Although they differ in details, these theories all propose that WM capacity cannot be adequately defined as simply how much information can be stored, but must also consider the control of access to this storage.

The notion that an executive control mechanism determines what information should be passed on to short-term storage is reminiscent of attentional selection, and has led numerous investigators to question whether the mechanisms involved in selectively attending to task-relevant information are very similar, or even identical, to those involved in selecting which information is held in WM (e.g., E. J. Anderson, Mannan, Rees, Sumner, & Kennard, 2010; J. R. Anderson, Matessa, & Lebiere, 1997; Awh & Jonides, 2001; Awh et al., 2006; Baddeley, 2012; Bundesen, 1990; Chun, Golomb, & Turk-Browne, 2011; Chun & Johnson, 2011; Cowan, Elliott, Scott Saults, et al., 2005; Desimone &
Duncan, 1995; Duncan & Humphreys, 1989; Engle & Kane, 2004; Gazzaley & Nobre, 2012; Lamme, 2000; Lavie, 2010; Lavie et al., 2004; Logan & Gordon, 2001; E. K. Miller & Cohen, 2001; Petersen & Posner, 2012; Vogel & Awh, 2008). For example, Lavie et al.’s (2004) cognitive load theory argues that a range of cognitive control abilities, including the inhibition of attentional capture by distracting stimuli and the control of access to WM, depend on the availability of cognitive control resources located in prefrontal cortex (see also E. K. Miller & Cohen, 2001; E. K. Miller, Li, & Desimone, 1991). Various theories of attention assert that selective attention involves maintaining a target template containing information about task-relevant locations or stimulus features, and suggest that this task is carried out by the same mechanisms involved in other WM tasks (e.g., Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Pashler & Shiu, 1999; Wolfe, 1994). Others argue that the mechanisms involved in selecting which information gains access to WM – Baddeley’s central executive – are in fact identical to those involved in selectively attending to task-relevant sensory information (e.g., Cowan, 1988; Cowan, Elliott, Saults, et al., 2005; Engle, 2002; Oberauer, 2009). Others go so far as to suggest that the construct of WM is essentially nothing more than the consequence of directing selective attention toward internally rather than externally generated stimulus representations (Chun, 2011; Kiyonaga & Egner, 2013; Nobre et al., 2004; Postle, 2006). Common to all of these theories is the notion that selective attention and WM are subserved by overlapping executive control networks. In the following sections I review some of the research that has investigated this claim.

1.3.2. Behavioural evidence for links between selective attention and working memory

A common strategy for investigating the relationship between selective attention and WM has been to look for correlations in individual differences in performance on separate measures of WM and selective attention. For example, Kane, Bleckley, Conway, and Engle (2001) compared performance on Daneman and Carpenter’s (1980) reading span test with performance on an antisaccade task, which requires observers to inhibit oculomotor capture by a salient onset cue and make an eye movement, or saccade, to a different location instead. Participants who performed poorly on the reading span test were more likely to fail to inhibit oculomotor capture by the onset cue (see also Unsworth, Schrock, & Engle, 2004). There was no such correlation between reading span scores and performance on a prosaccade task, which requires observers to saccade directly to the onset cue, suggesting that the relationship was specific to the ability to inhibit or control involuntary orienting, as opposed to involuntary orienting per se. Reading span performance also correlates with a variety of other measures of attentional control (for reviews, see Engle, Kane, et al., 1999; Kane & Engle, 2003). Numerous measures of selective attention have also been found to
correlate with performance on the operation span (O-Span) task, a WM-capacity measure that is similar to the reading span task in that it requires participants to build up a list of words, but which intersperses the words with math problems rather than with sentence reading to tax executive control mechanisms (for reviews, see Colzato, Spape, Pannebakker, & Hommel, 2007; Engle, 2002). For example, Conway, Cowan, and Bunting (2001) found poor performers on the O-Span task were more susceptible to the *cocktail party phenomenon*, whereby listeners tasked with selectively attending to and reproducing only one of two concurrently presented streams of speech are distracted from their task if their own name is presented in the ignored stream (Moray, 1959). Bleckley, Durso, Crutchfield, Engle, and Khanna (2003) found poor performers on the O-Span task also tended to perform poorly on another measure of selective attention, which required participants to search for a target letter within one of three concentric rings of letters and ignore distractor letters in the other rings. Overall, these findings suggest that a common capacity limitation influences individuals' performance on both WM and selective attention tasks, that generalises across different WM tasks and across sensory modalities.

The research described in the previous paragraph suggests a link between WM capacity and the ability to selectively attend to only task-relevant spatial locations. Other research has found some evidence for links between WM capacity and feature-based attention. Fukuda and Vogel (2011) investigated the relationship between feature-based attention and the VSTM component of WM capacity. Their feature-based attention task, illustrated in Figure 1-5, required participants to identify a target item of a specific colour in a search array (shown for green in the figure). The search array was sometimes preceded by a distracting flanker item of either the target colour (relevant flanker) or a different colour (irrelevant flanker). Responses to the target item were less accurate when preceded by a relevant relative to irrelevant flanker item, in line with previous behavioural evidence for contingent capture (e.g., Folk & Remington, 1998). This effect was greatest when there was a very short flanker-target SOA, and reduced with increasing SOA, suggesting a gradual recovery from contingent capture over time. To test for a link between feature-based attention and VSTM capacity, Fukuda and Vogel compared the time course of this contingent capture effect between participants who scored high versus low on a separate change detection task, which required participants to hold the colours and locations of a set of squares in memory over a short retention interval (see Luck & Vogel, 1997). High- and low-VSTM capacity groups were equally susceptible to interference by the task-relevant flanks at the shortest SOA, but the high-VSTM capacity group displayed significantly less interference at the second SOA, indicating that they had recovered from contingent capture to a greater extent by this point in time. These findings suggest that, although the VSTM component of WM capacity does not influence the initial
contingent capture of attention, it does influence the time-course of subsequent disengagement once contingent capture has taken place.

Bengson and Mangun (2011) also examined the relationship between feature-based attention and WM capacity. Unlike Fukuda and Vogel (2011), they used a measure of WM capacity designed to index both STM and central executive performance; the previously described O-Span task (Turner & Engle, 1989). To measure selective attention, Bengson and Mangun used a modified cueing paradigm in which participants had to report the spatial frequency of a target grating that could be presented to the left or right of fixation, and could be oriented horizontally or vertically. Prior to the appearance of the grating, participants were given partially predictive cues that indicated both the most likely location and most likely orientation of the upcoming target. Importantly, as the cues were partially predictive and there was a cue-target SOA of 800 – 1000 ms, any cue validity effects in this paradigm are likely to reflect the voluntary allocation of attentional resources, as opposed to involuntary attentional capture. The cue validity effect associated with the orientation cue correlated significantly with performance on the O-Span task, but only on trials in which the spatial cue was valid. Bengson and Mangun speculated that WM capacity might only correlate with feature-based
attention tasks when they require the integration of information across multiple dimensions- in their case, location and orientation. This explanation is in line with feature integration theory (Treisman & Gelade, 1980), which holds that the primary role of attention is to integrate information across feature dimensions.

As the studies described above by Fukuda and Vogel (2011) and Bengson and Mangun (2011) are the only two published studies to date that have directly investigated the link between WM capacity and feature-based attention, further research is necessary to gain a more thorough understanding of the nature and extent of this link. I set out to address this gap in the literature in Chapter 5 by investigating the relationship between the contingent capture effect and the central executive component of WM capacity, using both behavioural and electrophysiological measures of attentional capture.

Rather than using a correlational approach, in which WM capacity and attention are measured separately, other researchers have examined whether selective attention is compromised when observers perform a concurrent task that taxes WM. For example, Lavie et al. (2004) had participants perform an irrelevant flanker task (Eriksen & Eriksen, 1974) during the retention interval of a digit rehearsal task, which required them to hold a set of digits in memory. Increasing the number of digits in the set increased the behavioural interference associated with incongruent flanker items, suggesting that allocating more memory resources to the digit rehearsal task compromised the ability the selectively attend to only the central target letter in the irrelevant flanker task (see also De Fockert, Rees, Frith, & Lavie, 2001). Similar digit rehearsal manipulations of memory load have also been found to influence other behavioural measures of selective attention, including distractor interference in Theeuwes’s (1992) additional singleton paradigm (Lavie & De Fockert, 2005) and subsequent recognition of task-irrelevant distractor faces presented in the periphery during a word categorisation task (Carmel et al., 2012; see also Boot, Brockmole, & Simons, 2005; De Fockert & Bremner, 2011). It is interesting to note that, as with the measure of VSTM capacity used by Fukuda and Vogel (2011), the digit rehearsal manipulations used in these studies ostensibly only required the information storage – or STM – component of WM. At first glance, these findings appear to contradict theories that suggest the link between selective attention and WM is primarily driven by the central executive component of WM. One possibility is that these studies found an effect of STM load on measures of selective attention because having participants perform the two tasks concurrently caused the central executive to distribute the allocation of STM capacity between them.
Other studies of WM load indicate that concurrently performed STM and selective attention tasks do not interfere with each other when one of the tasks can be performed without the involvement of the central executive. For example, Woodman, Luck, and Schall (2007) had participants detect the presence of a “U” shape rotated in a specific direction from within an array of differently-oriented “U” distractors. Performance efficiency on this visual search task was measured using search slopes; the rate of change in RTs as the set size or number of items in the search array increases. To impose a VSTM load, the search arrays were sometimes presented during the retention interval of a coloured-square change-detection task. If the target rotation changed on every trial, necessitating the involvement of the central executive to maintain an up-to-date target template, performing the concurrent VSTM task significantly impaired visual search performance. By contrast, if there was a constant target orientation on every trial, the VSTM task had no effect on visual search performance (see also Woodman, Vogel, & Luck, 2001). The authors suggested that under these conditions, a target template for the visual search task could be transferred to LTM, freeing up central executive resources to focus exclusively on the VSTM task (see also Cowan, 2001; Hollingworth & Maxcey-Richard, 2013). Further evidence that two tasks will only interfere if they require access to executive control resources at the same time was provided by Woodman and Vogel (2005). They used a modified change detection paradigm in which the to-be-remembered array was backward masked after a variable SOA to provide an indication of the speed at which information could be consolidated into VSTM. Consolidation speed on the primary change detection task was not affected by presenting participants with two additional items to hold in memory 1.5 s prior to the primary memory array. The authors argued that the secondary task did not interfere with the primary task because participants had enough time to consolidate the additional items into STM prior to the primary memory array appearing, once again freeing up executive control resources to focus exclusively on the primary task.

In addition to the extent to which two concurrently performed tasks require central executive resources, it is also clear that the specific information content relevant to performing each task influences whether they will interfere with each other. For example, Woodman and Luck (2004) performed a study similar to the one described above by Woodman et al. (2007), in which participants performed a visual search task during the retention interval of a change detection task. In the earlier study, however, they used a change detection task in which participants had to remember the locations of a set of black squares, whereas in the later one the change detection task required participants to remember the colours of a set of squares in fixed locations. Unlike the colour task, the location task did interfere with the visual search task even when the visual search target was identical on each trial. The authors interpreted these findings as evidence that visual
search tasks that require sequential shifts of spatial attention are prone to interference from STM
tasks if they require the maintenance of spatial- but not featural- information (see also Oh & Kim,
2004). In a series of experiments, S. Y. Kim, Kim, and Chun (2005) provided further evidence that
STM load tasks can have different influences on selective attention tasks depending on the nature of
the information being remembered. In one study, participants performed a Stroop task that required
them to selectively process the meaning of a coloured word (e.g., “RED”) while ignoring the font
colour it was printed in. The interference produced by the distracting font colour information was
measured as a Stroop interference effect, or the extent to which RTs were slower when the meaning
and font colour were incongruent (e.g., the word “RED” printed in blue) relative to congruent (e.g.,
the word “RED” printed in red). The Stroop interference effect was increased when participants
were required to concurrently hold a series of letters in memory, which the authors suggested
interfered with participants’ ability to process the meaning of the coloured word. Holding the
locations of a series of black squares in memory did not similarly increase the Stroop interference
effect. The findings of this and other experiments conducted by S. Y. Kim et al. (2005) support the
notion that WM tasks that do not require the central executive can still interfere with selective
attention tasks if they involve the maintenance of similar information as is required to complete the
selective attention task (see also Konstantinou, Beal, King, & Lavie, 2014; Konstantinou & Lavie,
2013).

Further evidence indicating a functional link between WM and selective attention has come from
studies suggesting that the contents of VSTM influences perception and attentional selection (for a
review, see, Kiyonaga & Egner, 2013; but see Cosman & Vecera, 2011). In one early
demonstration, Pashler and Shiu (1999) had participants search through a RSVP stream of images
for a target digit while holding in mind a visual representation of a specific object (e.g., a tiger).
Participants were informed that one of the images in the stream would portray the object they were
imagining, and that they should ignore this and all other images in the stream. Nevertheless,
participants were less accurate in identifying the target digit when the imagined object appeared two
items before, relative to after, the target digit. The authors interpreted this as evidence that the
presence of the task-irrelevant imagined object evoked an attentional blink, a phenomenon whereby
allocating attentional resources to one object impairs the ability to allocate resources to a second
object appearing less than ~500 ms afterwards (Donald E. Broadbent & Broadbent, 1987; Raymond,
Shapiro, & Arnell, 1992). There is also evidence that visual stimuli that match the contents of
VSTM can involuntarily capture spatial attention to their location. Downing (2000) presented
participants with a face to hold in memory so they could report whether it was the same as or
different to a face presented several seconds later. During the retention interval, observers made a
speeded response to the orientation of a rotated “U” that could appear at one of two peripheral locations. Briefly prior to the “U” appearing, a task-irrelevant face appeared at each of the two peripheral locations; one matched the remembered face and the other was novel. Even though the location of the remembered face was not predictive of the location of the upcoming target, RTs were faster when the target appeared at the same location as the remembered face, suggesting it had captured attention to its location. Other studies using visual search paradigms have found that the presence of distractor stimuli matching items held in memory (for the purposes of a secondary task) can slow target responses and capture eye movements to their location, much like the presence of salient but task-irrelevant additional singletons (Hollingworth & Luck, 2009; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006). Such effects are not apparent if (a) the secondary memory task is completed prior to the presentation of the search array, or (b) the memory task stimuli are presented but participants are not required to remember them. These findings suggest that it is the process of actively maintaining the memory that leads to the effect rather than mere exposure or stimulus history (Pan, Xu, & Soto, 2009; Soto, Wriglesworth, Bahrami-Balani, & Humphreys, 2010).

As pointed out by Woodman and Luck (2007), however, although the studies described in the previous paragraph demonstrated an influence of VSTM contents on attentional selection, this influence might not have been involuntary. It could have resulted from participants voluntarily attending to visual stimuli matching their memory contents to improve their performance on the memory task. Woodman and Luck (2007) tested this possibility in a series of experiments in which participants search for a rotated “U” of a specific orientation in a search array of differently rotated and coloured “U”s while holding one or more rotated and coloured “U”s in memory for a second change detection task. In one experiment, the target item in the search task could have the same identity (rotation and colour) as the remembered item(s) for the change detection task. Under these conditions search task RTs were fastest when the target had the same identity as a remembered item and slowest in the presence (versus absence) of a remembered item as a distractor in the search array, consistent with the studies outlined above. In other experiments, observers knew in advance that the target item in the search task would never have the same rotation or colour as the remembered item(s) for the change detection task. Under these conditions search task RTs were fastest in the presence (versus absence) of a remembered item as a distractor in the search array. The authors interpreted this as evidence that when observers knew the items being remembered for the change detection task would never correspond to the target item in the search task, they voluntarily suppressed processing of, or attentional capture by, items matching the contents within VSTM (see also Downing & Dodds, 2004; Sawaki & Luck, 2011; for further discussion, see
Kiyonaga & Egner, 2013; Woodman & Luck, 2010). B. Zhang, Zhang, Huang, Kong, and Wang (2011) provided additional evidence that the relationship between VSTM contents and attentional capture is not automatic by demonstrating that the contents of VSTM no longer influence visual search performance under high VSTM load.

The behavioural studies described in this section have provided several lines of evidence to suggest that processes of selective attention and WM often interfere with each other, presumably because they compete for common executive control resources. As with the behavioural investigations of the influence of feature-based attention on attentional capture discussed in Section 1.2, however, different interpretations of the results of behavioural studies have led to a variety of hypotheses about the specific processing stages and brain regions involved in the interactions between selective attention and WM (for a discussion, see Awh et al., 2006). As noted earlier, however, behavioural studies on their own can be limited in the extent to which they are able to test such hypotheses. To more comprehensively investigate the neural basis of links between selective attention and working memory, many researchers have employed non-behavioural techniques such as EEG, fMRI, TMS, and lesion studies, which are reviewed in the following sections.

1.3.2. Electrophysiological evidence for links between selective attention and working memory

Vogel et al. (2005) used EEG to investigate the hypothesis that individual differences in WM capacity are more related to differences in the ability to control access to WM rather than to differences in STM capacity (e.g., Baddeley, 1992; Daneman & Carpenter, 1980). They used the change detection task illustrated in Figure 1-6a. Participants were presented with a set of two or four red bars in either the left or right visual field, which they had to compare against a test array presented after a retention interval. On some trials containing only two red bars, two additional task-irrelevant blue bars were presented. During the retention interval, Vogel et al. recorded the contralateral delay activity (CDA), an electrophysiological marker of the amount of information being held in STM (Vogel & Machizawa, 2004). Based on participants’ behavioural performance on the change detection task, the authors undertook a median split of participants into high and low WM capacity groups. When no task-irrelevant blue bars were present, there was a larger CDA evoked by four, relative to two, red bars in both groups of participants. The groups differed, however, in terms of the CDA recorded when there were two red bars and two blue bars. The CDA evoked in this condition for the high capacity group was similar to that evoked when the two red bars were presented on their own, whereas for the low capacity group it was more similar to that evoked when there were four red bars. The same pattern of results was observed when the task-
relevant bars were defined on the basis of location rather than colour. These findings suggest that the superior performance of the high WM capacity individuals was due to their superior ability to selectively exclude the task-irrelevant blue bars from gaining access to WM, as opposed to them simply having a larger STM capacity. Subsequent studies have provided corroborating evidence for this possibility by demonstrating correlations between WM capacity and the suppression of early visual ERPs associated with task-irrelevant distractors (Rutman, Clapp, Chadick, & Gazzaley, 2010; Zanto & Gazzaley, 2009).

Figure 1-6 Paradigm and results of Vogel et al. (2005). (a) Participants were cued to remember the locations and orientations of all the red bars on either the left or right half of a memory array. Each half of the memory array could contain: two red items on their own; four red items on their own; or two red items with two blue distractor items (as in the example above). After a retention interval, a test array was presented and participants had to report whether the red bars they were holding in memory were identical (as in the example above), or had changed orientation. (b) Contralateral delay activity (CDA) results for the three memory array conditions, separately for high and low WM capacity groups. For high capacity individuals (left plot), the CDA evoked by two target items plus two distractors (the red line) was more similar to the CDA evoked by two target items on their own (the black line). By contrast, for low capacity individuals (right plot), the CDA evoked by two target items plus two distractors was more similar to the CDA evoked by four target items (the blue line). Figure modified from Vogel et al. (2005).

Other studies have used EEG to extend on previous findings of greater distractor interference under high WM load (e.g., Lavie et al., 2004) by investigating how early in the time course of perception
the effects of WM load on distractor processing arise. Rose, Schmid, Winzen, Sommer, and Buchel (2005) varied WM load by having participants perform an n-back task on an RSVP stream of letters presented at fixation. The n-back task (Chatham et al., 2011; Kirchner, 1958) requires participants to monitor a stream of items for instances of the same item being repeated n positions apart. Performing this task requires participants to hold a list of n previous items in STM, update this list every time a new item appears, and compare each new item to the appropriate item in the remembered list. Thus, the n-back task places demands on both STM and central executive components of WM, to an extent that increases with the value of n. Rose et al. (2005) looked for an influence of the n-back WM load manipulation on early visual ERPs evoked by task-irrelevant background images of variable visibility. The N1 component evoked by the background images was less sensitive to image visibility when observers were performing a high load 2-back task than when they were performing a low load 1-back task, which the authors interpreted as evidence that taxing WM compromised early stages of object identification. They supported this interpretation by demonstrating, via source localisation (Pascual-Marqui, Michel, & Lehmann, 1994) and a complementary fMRI study, that the early effect of WM load on the N1 component was likely to have originated in the lateral occipital complex (LOC), part of the visual cortex implicated in processing object structure and identity (Grill-Spector, Kushnir, Hendler, & Malach, 2000; Kourtzi & Kanwisher, 2000). These findings suggest that taxing WM can affect very early stages of distractor stimulus processing (see also D. E. Anderson, Vogel, & Awh, 2013; Cocchi et al., 2011), as was found in the previously described EEG studies of feature-based attention (e.g., Zhang & Luck, 2009).

1.3.3. Neuroimaging evidence for links between selective attention and working memory

The effect of WM load on distractor stimulus processing has also been investigated using fMRI. De Fockert et al. (2001) had participants perform a Stroop-like task which required them to selectively attend to and categorise printed names of famous people as either politicians or musicians, while ignoring face images of famous people whose category could be congruent or incongruent with the printed name they appeared behind. To manipulate STM load, this categorisation task was performed during the retention interval of a digit rehearsal task that required participants to hold 5 chronologically ordered (low load) or randomly ordered (high load) digits in memory. Name-face congruency had more of an effect on RTs under high, relative to low, STM load, in line with previously described evidence for greater distractor interference under high STM load (e.g., Lavie et al., 2004). Additionally, BOLD responses to the distractor faces in extrastriate visual cortex and face selective fusiform gyrus were larger under high STM load, suggesting the effects of STM load
on distractor processing extend down to hierarchically early regions of visual cortex (see also Rissman, Gazzaley, & D'Esposito, 2009). Rose et al. (2005) also found larger BOLD responses in early occipital cortex under high WM load, using the previously described n-back manipulation designed to tax both STM and central executive components of WM. In a follow-up study, Klemen, Büchler, Bühler, Menz, and Rose (2010) found a similar effect even when the n-back task involved an aurally rather than visually presented letter stream, suggesting that the effect of WM load on visual stimulus processing originates in central, modality-unspecific brain regions. Further evidence for hierarchically early effects of WM comes from studies showing that the contents of VSTM can influence activity as early as primary visual cortex (V1) even in the physical absence of the remembered visual stimulus (Harrison & Tong, 2009; Malecki, Stallforth, Heipertz, Lavie, & Duzel, 2009; Munneke, Heslenfeld, & Theeuwes, 2010; Pasternak & Greenlee, 2005). Thus, similar to previously described fMRI studies of feature-based attention (e.g., Serences et al., 2005), evidence suggests that WM can modulate perceptual processing in hierarchically early regions of visual cortex.

Other studies indicate that, again similar to feature-based attention, early effects of WM on stimulus processing are driven by activity in frontal and parietal executive control networks. One common method for investigating the neural basis of WM has been to identify brain regions whose activity scales with WM load or WM task performance. These studies have used both fMRI and positron emission tomography (PET), and consistently indicate that WM involves a distributed network of areas in similar regions of prefrontal and posterior parietal cortices as have been implicated in selective attention (for reviews, see Fletcher & Henson, 2001; Gazzaley & Nobre, 2012; Wager & Smith, 2003). These executive control regions are active during both stimulus encoding (Gazzaley, 2011) and also information maintenance stages of WM tasks (Lepsien & Nobre, 2006; Postle, Awh, Jonides, Smith, & D'Esposito, 2004), suggesting that their role is not limited to sensory selection processes. This notion is also supported by functional connectivity analyses that have found enhanced connectivity between frontoparietal executive control regions and occipitotemporal perceptual regions during both encoding and maintenance stages (Gazzaley, Rissman, & D'Esposito, 2004; Honey et al., 2002). A number of studies have directly compared BOLD responses between tasks designed to require only spatial attention (e.g., covertly shifting attention in the direction of an arrow cue) and tasks designed to require only WM (e.g., comparing different difficulty levels of an n-back task), and have found a high degree of overlap in the frontal and

9 In addition to frontal and parietal cortical areas, subcortical areas including the basal ganglia have also been implicated in executive control of WM (McNab & Klingberg, 2008).
parietal brain regions activated by these very different tasks (LaBar, Gitelman, Parrish, & Mesulam, 1999; Smith & Jonides, 1999; Smith, Jonides, Marshuetz, & Koepppe, 1998).

The notion that, as with feature-based attention, WM influences activity in early visual cortex via executive control regions in prefrontal cortex, is also supported by invasive electrophysiological recording studies in monkeys. These studies have used delayed match-to-sample tasks, in which monkeys are trained to hold a presented image in memory so they can make a saccade to the same image if it appears again in a different location after a delay period. The identity of the image held in memory influences the firing rates of visual cortical neurons as early as area V4, across the entire delay period (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993; Hayden & Gallant, 2013). Complementary studies have similarly found the activity of neurons in prefrontal cortex are influenced by VSTM contents throughout the delay period (Everling, Tinsley, Gaffan, & Duncan, 2002; E. K. Miller, Erickson, & Desimone, 1996; Rainer, Asaad, & Miller, 1998).

1.3.4. Neurostimulation evidence for links between selective attention and working memory

Just as TMS has been used to investigate the causal role of frontoparietal control networks in feature-based attention (e.g., Schenkluehn et al., 2008), it has also been used to investigate the causal role of these control areas in WM. Zanto, Rubens, Thangavel, and Gazzaley (2011) applied repetitive trains of TMS pulses to a region of the prefrontal cortex previously implicated in the top-down modulation of activity in visual cortex, the right inferior frontal junction (IFJ), with the aim of disrupting activity in that region. Participants were then presented with a series of four dot-fields – two grey and moving coherently in one of 12 possible directions, and two static and all coloured in one of six possible colours – and had to remember either the two motion directions or the two colours. After a retention interval of 4 – 8 s, participants were presented with a probe dot field and had to report whether it matched one of the two feature values they were holding in memory. Relative to a sham TMS control (in which the TMS coil was held perpendicular to the head during stimulation such that the resulting magnetic field no longer substantially penetrated the skull), repetitive TMS of the right IFJ reduced participants’ accuracy in reporting which colours matched the ones they were holding in memory (see also Postle et al., 2006), which suggests WM requires a network that includes the right IFJ.

Other studies have investigated the role of prefrontal and parietal cortices in WM using a different neurostimulation technique called transcranial direct current stimulation (tDCS; for reviews, see
Brasil-Neto, 2012; Filmer, Dux, & Mattingley, 2014). This technique involves delivering a low intensity current between a pair of rubber electrodes placed on the scalp (Antal, Nitsche, & Paulus, 2006). Two factors arguably make tDCS better suited to investigating the role of prefrontal cortex in WM than TMS. First, tDCS appears to modulate activity in larger patches of cortex than TMS, which is appropriate given the widely distributed areas of prefrontal and parietal cortices implicated in WM by fMRI studies. Second, tDCS is subjectively less noticeable than TMS, and the proximity of prefrontal cortex to the facial muscles means targeting it with TMS can lead to uncomfortable face twitches in some participants. Marshall, Molle, Siebner, and Born (2005) found stimulating prefrontal cortex with tDCS reduced participants’ accuracy on a Sternberg task (Sternberg, 1966), which requires participants to hold a set of items in memory and then report whether each item in a subsequently presented stream of items belongs to the remembered set (see also Gladwin, den Uyl, Fregni, & Wiers, 2012). A number of subsequent studies have similarly found that tDCS of prefrontal cortex influences performance on other measures of WM capacity, including n-back tasks (Fregni et al., 2005; Mulquiney, Hoy, Daskalakis, & Fitzgerald, 2011; Ohn et al., 2008; Zaehle, Sandmann, Thorne, Jancke, & Herrmann, 2011) and digit rehearsal tasks (Andrews, Hoy, Enticott, Daskalakis, & Fitzgerald, 2011)\(^\text{10}\). Other studies have found tDCS of parietal cortex also influences performance on both n-back tasks (Sandrini, Fertonani, Cohen, & Miniussi, 2012) and image rehearsal tasks (Berryhill, Wencil, Branch Coslett, & Olson, 2010). One limitation of these neurostimulation studies, however, is that because the stimulation was applied ‘offline’ (i.e., well separated in time from the task of interest), no conclusions can be drawn about the specific stage(s) of task performance that were affected. That is, it is uncertain as to whether stimulation impacted stimulus selection, encoding, maintenance or retrieval. Nevertheless, they do represent causal evidence that distributed networks in frontal and parietal cortices are involved in at least some aspects of WM task performance.

\subsection*{1.3.5. Lesion evidence for links between selective attention and working memory}

Damage to frontal and parietal cortices has also been found to impair performance on WM tasks. Patients with frontal lobe damage display impairments on the Wisconsin card sort task (WCST),

\footnote{Many of these subsequent studies found WM task performance to be facilitated rather than impaired following prefrontal tDCS. These findings are not necessarily contradictory, however. The effects of tDCS – and in fact neurostimulation techniques in general – can change with various paradigm factors, such as the location and polarity of the electrodes, the intensity and duration of stimulation (Antal et al., 2006). The activity changes brought about by neurostimulation techniques can include both increases and decreases in regional excitability and resting membrane potentials (Hoogendam, Ramakers, & Di Lazzaro, 2010; Miniussi et al., 2010; Ziemann, 2010), and so the techniques are capable of both improving and impairing task performance, depending on the specific experimental parameters.}
which involves sorting cards according to their shape, colour, or number of items, with the sorting rule varying periodically (Milner, 1963). Patients with frontal lobe damage also perform poorly on Stroop tasks (Cohen & Servanschreiber, 1992; Vendrell et al., 1995), suggesting impairments in the ability to selectively attend to either the colour or meaning of written words. Further, their performance is particularly poor when they have to frequently switch between reporting the colour and meaning of the words (Dunbar & Sussman, 1995), suggesting additional impairments in WM (recall that task switching is another process attributed to the central executive; see also Nagahama et al., 2001). Experimentally lesioning or temporarily deactivating prefrontal cortex in monkeys has also been found to impair WM performance as measured using delayed match-to-sample tasks (Curtis & D'Esposito, 2004; Goldman, Rosvold, Vest, & Galkin, 1971; Mishkin & Manning, 1978; Passingham, 1975), card sorting tasks (Dias, Robbins, & Roberts, 1996, 1997) and other tasks that require switching between rules (A. Rossi, Rotter, Desimone, & Ungerleider, 1999). Other studies have found that patients with damage to posterior parietal cortex are impaired on a variety of WM tasks, including recalling a series of images or aurally delivered words in the correct order (Berryhill, Chein, & Olson, 2011; Berryhill & Olson, 2008). Overall, the diverse range of evidence reviewed above suggests that, like feature-based attention, WM involves modulations of processing in early sensory areas, and also depends on activity in executive control networks in prefrontal and parietal cortices.

### 1.4. Summary and thesis goals

Some theories of attention (e.g., Cave & Wolfe, 1990; Theeuwes, 1992; Treisman & Sato, 1990) assume that involuntary attentional capture, as its name suggests, is essentially an automatic process, determined solely by physical aspects of the external environment. In contrast to these theories, research reviewed in this chapter suggests that the extent to which visual stimuli capture attention is heavily dependent on internal factors. One such factor is feature-based attention, or the visual features an observer is monitoring for during a visual search task (e.g., Folk et al., 1992). Another factor shown to influence attentional capture is WM, or the information an observer is currently holding, manipulating, and updating in short-term memory (e.g., De Fockert et al., 2001). Other theories of attention (e.g., Desimone & Duncan, 1995; Lavie et al., 2004) propose that these ‘top-down’ influences on ‘bottom-up’ attentional capture occur because central executive control networks in prefrontal and parietal cortices send signals to sensory networks in occipital and temporal cortices, biasing them to process certain stimuli at the expense of others. This proposal is now well supported by evidence from a variety of different investigative techniques (for reviews,

One prediction that arises from theories that suggest that common resources are responsible for controlling a wide variety of processes is that performing more than one of these processes should lead to a competition for shared resources, resulting in impaired performance of one or more of the processes. My thesis tests this prediction by examining whether two specific executive control processes – feature-based attention and WM – interfere with each other in terms of their effects on attentional capture. In Chapter 2, I describe an experiment in which a novel paradigm was designed and validated, which allowed: (a) the manipulation of both feature-based attention and WM during a sustained visual monitoring task, and (b) the measurement of both behavioural and electrophysiological indices of attentional capture. Chapters 3 and 4 examine whether the influence of feature-based attention on attentional capture (i.e., the contingent capture effect) is reduced under conditions of high concurrent WM load. For this investigation two different WM load manipulations were used; a digit rehearsal task designed to require only the STM component of WM, and an $n$-back task designed to require both the STM and central executive components of WM. This allowed me to test the possibility that contingent capture is only reduced by WM manipulations involving the central executive. In Chapter 5 an individual differences approach was used to test the same prediction of functional interdependence between feature-based attention and WM. Specifically, I asked whether individuals with high WM capacity also have a greater capacity to impose feature-based attentional control settings, resulting in a larger contingent capture effect. For this purpose three different measurements of WM capacity were made, which allowed me to test the possibility that links between feature-based attention and WM capacity are specific to certain components of WM. Chapter 6 concludes with a summary of my findings and how they relate to other research and current theoretical models, and offers directions for future research.
Chapter 2. An effect of task set on behavioural interference in a novel paradigm
2.1. Introduction

More than two decades of behavioural investigations have failed to conclusively resolve the debate over whether task set influences attentional capture, or only later stages of perceptual processing (Folk & Remington, 2006, 2010; Theeuwes, 2010; Theeuwes et al., 2000). I suggest that purely behavioural measures are unlikely to be able to resolve this debate, because rather than providing a direct index of attentional capture behavioural measures, such as RT and accuracy, reflect the endpoint in a set of perceptual, decisional, and response processes. Thus, proponents of the stimulus-driven capture theory will always be able to validly point out that any effect of task set on behaviour could have arisen at stages of processing later than attentional capture.

In addition to the controversy surrounding the use of behavioural measures as proxies for attentional capture, another factor that may have contributed to the lack of resolution of the stimulus-driven capture versus contingent capture debate is that the two theoretical camps have tended to use very different paradigms. Evidence used to support the stimulus-driven capture theory has often come from the irrelevant singleton paradigm. In this paradigm, observers search for a target item amongst an array of distractor items, one of which is sometimes a singleton on a task-irrelevant feature dimension (e.g., Theeuwes, 1991a, 1992). In contrast, evidence used to support the contingent capture theory has often come from the spatial cueing paradigm. Here, a target item is preceded by a spatial cue that either possesses or does not posses the target-defining feature. This cue can either appear at the same location as the upcoming target or a different location, and attentional capture is measured as the extent to which target responses are influenced by the location of the different cue types (e.g., Folk & Remington, 1998; Folk et al., 1992). It may be that differences between the irrelevant singleton paradigm and the spatial cueing paradigm have lead to patterns of results that cannot be readily reconciled. An unbiased investigation of the stimulus-driven versus contingent capture debate may require the use of a new paradigm.

I chose to develop a novel paradigm to investigate attentional capture in my PhD for two main reasons. The first was to attempt to move away from the traditional irrelevant singleton and spatial cueing paradigms, aspects of which might have been unintentionally contributing to the longevity of the stimulus-driven versus contingent capture debate. The second was to allow the investigation of attentional capture over extended periods of monitoring dynamic stimulus displays, which I argue is more representative of the of the ongoing search tasks we face in everyday life than the traditional paradigms. I also elected to use a sustained monitoring task rather than discrete, static displays, to avoid any effect of having stimuli suddenly onsetting and offsetting against a blank
background. In my novel paradigm, both target and distractor objects can appear within multiple possible stimulus streams, and can be defined by multiple feature values along multiple feature dimensions. I also designed the paradigm to allow measurement of both behavioural and electrophysiological indices of distractor processing. I presented distractors at lateralised locations so I could record the distractor-evoked N2pc (Luck & Hillyard, 1994b), an electrophysiological marker of visual spatial attention. I presented targets on the midline so that their presence would not interfere with the distractor-evoked N2pc, which allowed me to take behavioural and N2pc measures of distractor processing at the same time. I presented targets at one of two possible locations to encourage participants to adopt a distributed rather than focused attentional set. This decision was motivated by theories of attention that predict deploying attention over multiple objects or locations can facilitate the processing of stimulus features at unattended locations (e.g., Treisman, 2006).

The key divergence in predictions between the stimulus-driven and contingent capture theories lies in whether task set affects attentional capture, or only later stages of processing. Both theories predict, or at least allow for the possibility of, an effect of task set at the level of behaviour. Thus, before investigating any effects of task set and WM on attentional capture and associated neural responses, I wanted to demonstrate a reliable effect of task set on behaviour in my novel paradigm. This was the primary goal of the present experiment. In subsequent chapters, I go on to use this novel paradigm to investigate the interactive effects of task set and working memory on attentional capture, as measured using both behaviour and electrophysiology.

2.2. Method

2.2.1. Participants

Twenty staff and students (eight female, aged between 18 and 30 years) from The University of Queensland, Australia, took part in this experiment. All participants in all experiments reported normal or corrected-to-normal vision, and were screened for problems with colour vision using the Ishihara test for colour blindness. The University of Queensland Behavioural & Social Sciences Ethical Review Committee approved all procedures. I obtained written informed consent from participants prior to each testing session. Participants were financially reimbursed at a rate of AU$15 per hour.
2.2.2. *Stimuli and apparatus*

Visual stimuli were presented against a black (RGB coordinates 0, 0, 0) background on an LCD monitor at a screen resolution of 1280 × 1024 pixels and a refresh rate of 60 Hz. Participants were seated at a viewing distance of 60 cm from the monitor, maintained using a chin rest. Stimulus presentation and response recording were controlled using Cogent software (Cogent 2000 toolbox: FIL, ICN, and Wellcome Department of Imaging Neuroscience) in Matlab version 7.13 (www.mathworks.com), running on a desktop computer.

2.2.3. *Procedure*

Figure 2-1 illustrates the key elements of the novel paradigm I developed for this experiment. Participants fixated a gray (RGB 127, 127, 127) central plus sign 0.6° wide and high. Fields of 20 gray (RGB 150, 150, 150) moving square dots 0.1° wide and high were present above, below, left and right of fixation. Each dot field was enclosed in a gray (RGB 127, 127, 127) box 3° wide and high, centered 4° from fixation. Most of the time, each dot moved to a random new location within its bounding box 60 times per second, creating the appearance of dynamic noise. Occasionally, one of three events happened in one of the four locations; the dots turned red (RGB 110, 0, 0), turned green (RGB 0, 100, 0), or began moving radially outwards from the center of their bounding box. In separate sessions, participants were asked to fixate the central plus sign and covertly monitor for one of these three event types in the upper and lower locations, and ignore all events in the left and right locations. During each event in an attended (upper or lower) location, all dots in that location became horizontal or vertical bars 0.4° long and 0.1° thick. If these bars possessed the feature currently being looked for (red, green, or radial motion), the participant had to report their orientation (horizontal or vertical) by pressing one of two keys on the keyboard as quickly as possible. During events in an ignored (left or right) location, dots in that location became horizontal and vertical bars in equal proportions. Each of the attended event types was paired an equal number of times with each of four distractor conditions; no distractor, red distractor, green distractor, and motion distractor. Each possible combination of attended event type (none, red, green, motion), attended event location (upper, lower), attended event bar orientation (horizontal, vertical), distractor type (none, red, green, motion), and distractor location (left, right) occurred an equal number of times during each stimulus stream, which lasted approximately 2 minutes. Events in attended locations lasted for 167 ms, and distractor events lasted for 467 ms. Whenever an attended event was paired with a distractor event, both events began simultaneously. The onset asynchrony
between consecutive events was varied randomly between 1500 ms and 2500 ms (square distribution). I avoided having a fixed SOA so that observers could not predict when stimuli would appear, and also so that there would not be any influence on visual-evoked potentials produced by time-locking the preceding stimulus display.

Figure 2-1 Paradigm for Experiment 1. Observers fixated a central plus sign and covertly monitored dynamic stimulus streams above and below fixation for groups of either red bars or green bars (colour search), or bars moving radially outwards from the center of a bounding box (motion search). The specific feature used to define the target was varied between sessions. Groups of red, green, or radially moving bars were also presented within dynamic stimulus streams to the left and right of fixation, and served as distractors. Observers were instructed to ignore any bars presented in the left and right locations, and also to ignore any bars presented in the upper and lower locations that did not possess the current target feature. Their task was to report whether detected target bars were oriented horizontally or vertically as quickly and accurately as possible. Note that there were 20 objects per location in the actual experiment; there are only 4 objects per location in this figure for the sake of clarity.

Each participant completed two sessions: A colour search session and a motion search session. The order in which participants completed the two sessions was counterbalanced across participants. In the colour search session participants searched for either red or green target events (also counterbalanced across participants), and in the motion search session participants searched for
radial motion targets. In each session participants completed four practice streams and then 12 experimental streams. Online performance feedback was provided during the practice but not experimental streams (if a correct response was made to a target event, the letter “y” was briefly presented just above the fixation cross; if an incorrect response was made to a target event, the letter “n” was briefly presented just above the fixation cross; if a response was made in the absence of a target event, the word “absent” was briefly presented just above the fixation cross). At the end of each stream participants were informed of the percentage of target events they correctly responded to during that stream (hit rate), and their average RT on target events they responded to correctly.

2.3. Results

I conducted all statistical tests with a two-tailed overall alpha level of .05. Mauchly’s Test of Sphericity was applied to all within-subjects F tests. Greenhouse-Geisser epsilon adjustments were made to degrees of freedom for these F tests wherever the assumption of sphericity was untenable. Unadjusted degrees of freedom are reported for all F tests.

Figure 2-2 displays mean hit rates and RTs for each combination of search type (colour search; motion search), and distractor type (none; target-coloured, TC\textsuperscript{11}; non-target-coloured, NTC; motion). The two behavioural measures were subjected to separate 2 × 4 within-subjects ANOVAs with factors of search type and distractor type. Each participant was exposed to 48 target events for each of the eight cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For hit rates (Figure 2-2a), there was no significant main effect of distractor type, $F(3,57) = 1.70, p = .177$, or search type, $F(1,19) = 0.01, p = .945$, and no interaction between the factors, $F(3,57) = 2.53, p = .079$. Thus, there was no evidence for any effect of search type or distractor type on hit rates.

\textsuperscript{11} For each participant, the colour they monitored for during their colour search session was defined as the target colour, and the other colour was defined as their non-target colour. Note that these definitions had no direct relevance to the participants’ task in their motion search session.
For RTs (Figure 2-2b), a significant main effect of distractor type, $F(3,57) = 4.51, p = .007, \eta_p^2 = .192$, was qualified by a significant interaction between search type and distractor type, $F(3,45) = 7.69, p < .001, \eta_p^2 = .339$, suggesting that the pattern of interference associated with the different distractors varied across search tasks. There were significant simple effects of distractor type for both search types [colour search, $F(3,57) = 6.04, p = .001, \eta_p^2 = .241$; motion search, $F(3,57) = 5.07, p = .004, \eta_p^2 = .211$], which I followed up with within-subjects $t$ tests. As my primary goal with this experiment was to demonstrate an effect of task set on the behavioural interference associated with distractors, I had decided *a priori* to conduct within-subjects $t$ tests between the task-relevant distractor condition and the other three distractor conditions, separately for each search task.

For the colour search session, RTs were significantly longer in the TC distractor condition ($M = 633$ ms, $SE = 15$ ms) than in the no distractor condition ($M = 616$ ms, $SE = 15$ ms), $t(19) = 3.52, p = .002$, indicating that the presence of task-relevant TC distractors slowed target responses. Further, RTs were significantly longer in the TC distractor condition than in the NTC distractor condition ($M = 622$ ms, $SE = 16$ ms), $t(19) = 2.40, p = .027$, and the motion distractor condition ($M = 622$ ms, $SE = 16$ ms), $t(19) = 2.22, p = .039$. This indicates that the task-relevant TC distractors produced more behavioural interference than the task-irrelevant NTC and motion distractors.

For the motion search session, RTs were significantly longer in the task-relevant motion distractor condition ($M = 644$ ms, $SE = 18$ ms) than in the no distractor condition ($M = 629$ ms, $SE = 17$ ms), $t(19) = 3.33, p = .004$, indicating that the presence of task-relevant motion distractors slowed target responses. RTs in the motion distractor condition were also significantly longer than those in the TC distractor condition ($M = 630$ ms, $SE = 17$ ms), $t(19) = 2.48, p = .027$, but not the NTC
distractor condition ($M = 636 \text{ ms}, SE = 18 \text{ ms}$), $t(19) = 1.76, p = .094$, although the trend was in the predicted direction. Taken as a whole, these results indicate that task-relevant distractors tended to produce more behavioural interference than task-irrelevant distractors in both search sessions.

Note that, taken on their own, these behavioural results could plausibly have been driven by differences in how much participants shifted their eyes toward the distractors, rather than differences in attentional capture per se. In this experiment I made no attempt to ensure that participants did not move their eyes toward the distractor locations. In the subsequent experiments reported in Chapter 3, however, I used electro-oculogram (EOG) data to monitor eye movements, and to exclude trials in which their eyes moved toward the distractors.

2.4. Discussion

The aim of this experiment was to test whether I could elicit an effect of task set on behaviour in a novel paradigm developed to investigate the interactive effects of task set and WM on attentional capture. As predicted, distractors slowed behavioural responses to targets more when they possessed a feature relevant to an observer’s current search task\textsuperscript{12}. These findings replicate and extend previous evidence for an effect of task set on behaviour (e.g., Folk et al., 1992), demonstrating that the results observed previously in static onset displays generalize to situations involving the sustained monitoring of dynamic stimulus displays. The findings also indicate that my novel paradigm serves as a suitable platform for exploring the interactive effects of task set and WM on attentional capture, which I went on to do in the experiments reported in the following chapters.

\textsuperscript{12} It should be pointed out here that Experiment 1 of Chapter 3 is almost identical to the experiment reported here, except that (1) I recorded EEG data while participants were performing the tasks to allow me to measure the N2pc associated with the distractors, and (2) there were 20 experimental blocks per session, rather than 12. The behavioural results in Experiment 1 of Chapter 3 are consistent with those observed in this experiment: Neither search type nor distractor type influenced hit rates, but there was an interaction between these two factors on RTs such that for each search type, only the currently task-relevant distractor slowed behavioural responses.
Chapter 3. Interactive effects of task set and working memory load on attentional capture
3.1. Experiment 1

3.1.1. Introduction

As discussed in Chapter 1, involuntary attentional capture is influenced by both task set (what an observer is looking for; Folk et al., 1992; Lien, Ruthruff, & Cornett, 2010) and WM load (Lavie & De Fockert, 2005; Lavie et al., 2004). Numerous theoretical accounts suggest that selective attention and WM utilise, and compete for, similar populations of prefrontal neural resources (e.g., J. R. Anderson et al., 1997; Awh et al., 2006; Baddeley, 2003; Bundesen, 1990; Chun, 2011; Conway et al., 2001; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Lavie et al., 2004; Logan & Gordon, 2001; E. K. Miller & Cohen, 2001). In this chapter I test this assumption in a series of four experiments, by examining whether taxing WM compromises the extent to which attentional capture is biased toward task-relevant features. Before introducing a WM load, however, in Experiment 1 I verified that I could replicate previous electrophysiological evidence for contingent capture using the novel sustained monitoring paradigm I developed in Chapter 2.

3.1.2. Method

Participants

Sixteen staff and students (ten female, aged between 18 and 36 years) from The University of Queensland, Australia, took part in Experiment 1. All participants in all experiments reported normal or corrected-to-normal vision, and were screened for problems with colour vision using the Ishihara test for colour blindness. The University of Queensland Behavioural & Social Sciences Ethical Review Committee approved all procedures. I obtained written informed consent from participants prior to each testing session. Participants were financially reimbursed at a rate of AU$15 per hour.

Stimuli and apparatus

Visual stimuli were presented against a black (RGB coordinates 0, 0, 0) background on an LCD monitor at a screen resolution of 1280 × 1024 pixels and a refresh rate of 60 Hz. Participants were seated at a viewing distance of 60 cm from the monitor, maintained using a chin rest. Stimulus presentation and response recording were controlled using Cogent software (Cogent 2000 toolbox: FIL, ICN, and Wellcome Department of Imaging Neuroscience) in Matlab version 7.13 (www.mathworks.com), running on a desktop computer. These same stimuli and apparatus were used in all subsequent experiments in this chapter.
Procedure

Experiment 1 was very similar to the behavioural experiment reported in Chapter 2. To briefly recap, participants covertly monitored dynamic stimulus streams above or below fixation for either red or green bars (colour search session), or radially moving bars (motion search session). Their task was to report whether detected target bars were oriented horizontally or vertically as quickly and accurately as possible. Red, green, or radially moving bars were also presented within dynamic stimulus streams to the left or right of fixation, and served as distractors. For further details, see Chapter 2.2.3. There were two differences between this experiment and the behavioural experiment in Chapter 2. First, each session involved 20 experimental streams, rather than only 12. Second, I recorded electroencephalogram (EEG) data while observers were performing their tasks.

Electroencephalography

Continuous EEG data were recorded using a BioSemi Active Two system (BioSemi, Amsterdam, Netherlands), digitised at a 1024 Hz sample rate with 24-bit A/D conversion. The 64 active scalp Ag/AgCl electrodes were arranged according to the international standard 10–10 system for electrode placement (Oostenveld & Praamstra, 2001) using a nylon head cap. As per BioSemi system design, the Common Mode Sense and Driven Right Leg electrodes served as the ground, and all scalp electrodes were referenced to the Common Mode Sense electrode during recording. Eye movements were monitored using bipolar horizontal EOG electrodes placed at the outer canthi of each eye, and bipolar vertical EOG electrodes placed above and below the left eye.

Offline EEG data analysis was performed using Brain Electrical Source Acquisition (BESA 6.0; MEGIS Software GmbH, Gräfelfing, Germany) and a purpose-built Matlab script. The data for the scalp electrodes were re-referenced to the average of all 64 scalp electrodes, and subjected to a 0.1 Hz high-pass digital filter. Noisy channels, identified by visual inspection of the data, were replaced by a spherical spline interpolation of the voltages recorded at all other scalp electrodes (a maximum of five per participant). The data were then segmented into epochs from 100 ms before to 400 ms after the onset of each distractor event, with the average voltage in the 100 ms prestimulus interval serving as a baseline. Epochs in which the difference between the maximum and minimum voltage exceeded 120 µV at any channel were automatically rejected to remove epochs contaminated by blinks, eye movements and other artifacts. An average of 9% of epochs per participant were rejected for violating this criterion. The remaining epochs were then averaged together, separately
for each combination of search type (colour search, motion search), distractor type\(^\text{13}\) (target-coloured, TC\(^\text{14}\); non-target-coloured, NTC; motion), and distractor location (left, right). Data were then collapsed across the two distractor locations by separately averaging together waveforms from contralateral electrodes (electrodes left of the midline for distractors on the right, and electrodes right of the midline for distractors on the left) and ipsilateral electrodes (electrodes right of the midline for distractors on the right, and electrodes left of the midline for distractors on the left). An average of 291 epochs contributed to each waveform for each of the 16 participants and each of the six conditions.

3.1.3. Results

I conducted all statistical tests with a two-tailed overall alpha level of .05, and made Bonferroni corrections to this significance criterion for all post hoc pairwise comparisons. Mauchly’s Test of Sphericity was applied to all within-subjects F tests. Greenhouse-Geisser epsilon adjustments were made to degrees of freedom for these F tests wherever the assumption of sphericity was untenable. Unadjusted degrees of freedom are reported for all F tests. I applied these same statistical guidelines to all experiments in this chapter.

Behaviour

Figure 3-1 displays mean hit rates and RTs for each combination of search type (colour search, motion search), and distractor type (none, TC, NTC, motion). The pattern of RTs across distractor types varied between the two search types, but hit rates were roughly equivalent across the two search types. To test this statistically, the two behavioural measures were subjected to separate 2 × 4 within-subjects ANOVAs with factors of search type and distractor type. Each participant was exposed to 80 target events for each of the eight cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For hit rates (Figure 3-1a), a significant main effect of distractor type, \(F(3,45) = 4.08, \varepsilon = .65, p = .028, \eta^2_p = .214\), was followed up by within-subjects \(t\) tests with a Bonferroni corrected alpha of .008 (6 possible comparisons). Relative to the no distractor baseline \((M = 92.70\%, SE = 0.99\%)\) hit rates were significantly reduced in the presence of motion distractors \((M = 90.43\%, SE = 0.96\%), t(15) = 3.30,\)

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\(^{13}\) Note that there is no “no distractor” condition in the N2pc analysis, as an N2pc should not be evoked when there is no lateralised stimulus present.

\(^{14}\) For each participant, the colour they monitored for during their colour search session was defined as the target colour, and the other colour was defined as the non-target colour. Note that these definitions had no direct relevance to the participants’ task in their motion search session.
\[ p = .005, \text{ but unchanged in the presence of TC distractors } (M = 91.80\%, SE = 1.17\%), t(15) = 1.86, p = .083, \text{ or NTC distractors } (M = 92.58\%, SE = 0.87\%), t(15) = 0.19, p = .850. \] There was no significant main effect of search type, \( F(1,15) = 0.46, p = .510, \) and no interaction between the factors, \( F(3,45) = 1.51, \epsilon = .56, p = .240. \)

![Figure 3-1](image-url) Behavioural results for Experiment 1. (a) Hit rates. (b) Reaction times. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

For RTs (Figure 3-1b), a significant main effect of distractor type, \( F(3,45) = 6.62, \epsilon = .64, p = .005, \eta_p^2 = .306, \) was qualified by a significant interaction between the factors, \( F(3,45) = 7.69, p < .001, \eta_p^2 = .339. \) There were significant simple effects of distractor type for both search types [colour search, \( F(3,45) = 6.40, p = .001, \eta_p^2 = .299; \) motion search, \( F(3,45) = 7.63, p < .001, \eta_p^2 = .337 \)], which were followed up by within-subjects \( t \) tests with a Bonferroni corrected alpha of .008. During the colour search session, relative to the no distractor baseline (\( M = 638 \text{ ms, } SE = 21 \text{ ms} \)), RTs were significantly increased in the presence of TC distractors (\( M = 652 \text{ ms, } SE = 23 \text{ ms} \)), \( t(15) = 3.55, p = .003 \), but not in the presence of NTC distractors (\( M = 640 \text{ ms, } SE = 20 \text{ ms} \)), \( t(15) = 0.62, p = .543 \), or in the presence of motion distractors (\( M = 641 \text{ ms, } SE = 20 \text{ ms} \)), \( t(15) = 0.86, p = .402 \). In contrast, during the motion search session, relative to the no distractor baseline (\( M = 636 \text{ ms, } SE = 27 \text{ ms} \)), RTs were significantly increased in the presence of motion distractors (\( M = 655 \text{ ms, } SE = 28 \text{ ms} \)), \( t(15) = 3.81, p = .002 \), but not in the presence of TC distractors (\( M = 636 \text{ ms, } SE = 26 \text{ ms} \)), \( t(15) = 0.11, p = .913 \), or in the presence of NTC distractors (\( M = 637 \text{ ms, } SE = 26 \text{ ms} \)), \( t(15) = 0.32, p = .756 \). In sum, the behavioural results for this experiment exactly replicated those I observed in Chapter 2: For both search types, task-relevant distractors slowed RTs, whereas the other two task-irrelevant distractors did not.

**Electroencephalography**

Panels a – f of Figure 3-2 display the waveforms associated with each combination of search type (colour search, motion search), and distractor type (TC, NTC, motion) at electrodes PO7/8, lateralised relative to distractor location. Mean N2pc amplitude was defined as the average voltage
difference between the contralateral and ipsilateral PO7/8 waveforms between 200 and 280 ms post distractor onset. The mean N2pc amplitudes of each condition are plotted in Figure 3-2g. Mean N2pc amplitude was significantly different from zero in each of the six conditions (all \( p \leq .019 \)). As can be seen, the pattern of N2pc amplitudes across distractor types varied between the two search types. To test this statistically, N2pc amplitudes were subjected to a 2 × 3 within-subjects ANOVA with factors of search type and distractor type. A significant main effect of distractor type, \( F(2,30) = 4.41, p = .041, \eta^2_p = .227 \), was qualified by a significant interaction between the factors, \( F(2,30) = 24.74, p < .001, \eta^2_p = .623 \). The simple effect of distractor type was marginally significant for the colour search session, \( F(2,30) = 3.13, p = .058, \eta^2_p = .173 \), and significant for the motion search session, \( F(2,30) = 10.67, \epsilon = .64, p < .001, \eta^2_p = .416 \). Follow-up linear contrasts revealed that for the colour search session, TC distractors were associated with significantly larger N2pc amplitudes (\( M = -1.27 \mu V, SE = 0.17 \mu V \)) than NTC or motion distractors, \( t(15) = 3.03, p = .008 \), that did not differ from each other (\( M = -0.60 \mu V, SE = 0.16 \mu V \) and \( M = -0.83 \mu V, SE = 0.29 \mu V \) respectively), \( t(15) = 3.03, p = .488 \). In contrast, for the motion search session, motion distractors were associated with significantly larger N2pc amplitudes (\( M = -1.83 \mu V, SE = 0.42 \mu V \)) than TC or NTC distractors, \( t(15) = 3.49, p = .003 \), that did not differ from each other (\( M = -0.41 \mu V, SE = 0.14 \mu V \) and \( M = -0.32 \mu V, SE = 0.12 \mu V \) respectively), \( t(15) = 0.49, p = .632 \). Thus, for both of the search tasks, distractors that possessed the specific feature relevant to the observers’ task evoked a larger N2pc than distractors that did not. These results replicate previous findings of an effect of task set on the N2pc (e.g., Lien et al., 2008).
Figure 3-2 Event-related potential results for Experiment 1. (a – f) Grand average waveforms associated with the distractors at electrodes PO7/8 across the conditions of search type and distractor type, separately for the contralateral and ipsilateral waveforms relative to distractor location. The shaded boxes indicate 200 – 280 ms post stimulus onset, the time window used for the N2pc analyses. The topographical map accompanying each panel is a spherical spline interpolation of the average amplitude difference between the contralateral and ipsilateral waveforms over this time window. To combine data from both distractor locations for these topographical maps, I flipped the data associated with the right distractor location about the midline of the head. Thus, the topographical maps should be interpreted as if the distractors had always been presented in the left distractor location. (g) Mean N2pc amplitude associated with the distractors across the conditions of search type and distractor type. Error bars represent within-subjects standard errors of the means (Cousineau, 2005). Negative voltages are plotted upwards in all plots.

I conducted two additional analyses to investigate whether the observed N2pc effects could have resulted from eye movements rather than shifts of attention. First, to test whether each participant
systematically moved his or her eyes towards the distractor stimuli, I calculated the average amplitude between 200 and 280 ms after distractor onset (i.e., the N2pc time window) in the HEOG data, separately for left and right distractor presentations. The maximum absolute voltage over this time window in either direction in any participant was 1.27 µV, well within the standard threshold of ±3 µV used for rejecting participants due to excessive eye movements (e.g., Lien et al., 2010). Second, I subjected average amplitudes between 200 and 280 ms after distractor onset in the HEOG data to the same 2 × 3 within-subjects ANOVA applied to the N2pc data. There was no effect of search task or distractor type, and no interaction between the factors (all \( p \geq .241 \)), suggesting that the observed effects of the distractor stimuli on the N2pc were not a consequence of eye movements.

An incidental observation also deserves mention at this point. Visual inspection of the lateralised difference waveforms in Figure 3-2 suggests that the contralateral negativity associated with the motion distractors (e – f) may have commenced earlier than that associated with the colour distractors (a – d), irrespective of the observers’ task set. This observation may relate to previous findings of rapid orienting to inherently salient stimuli (e.g., van Zoest & Donk, 2005). This possibility will be discussed in greater detail in Section 3.3.3.

A potentially important difference between the paradigm used in this experiment and previous paradigms is that the majority of the distractor presentations occurred in the absence of a target event. One might ask whether the same pattern of results reported above would be observed if every distractor had occurred in the presence of a target event, as is more commonly the case in N2pc studies of attentional capture (e.g., Eimer & Kiss, 2008; Leblanc et al., 2008; Lien et al., 2008). To address this question, I conducted the same N2pc analysis reported above, but only including distractor events that were accompanied by a target event. An average of 70 epochs contributed to each waveform for each of the 16 participants and each of the six conditions in this new analysis. The resulting N2pc waveforms and mean N2pc amplitudes are plotted in Figure 3-3. Note that the pattern of N2pc amplitudes in this analysis is very similar to those observed for the full dataset (Figure 3-2). Subjecting these data to the same ANOVA applied to the full dataset yielded no main effect of search type, \( F(1,15) = 0.84, p = .375 \), or distractor type, \( F(2,30) = 2.56, p = .094 \). More importantly, however, there was still a significant interaction between the factors, \( F(2,30) = 11.29, p < .001, \eta_p^2 = .430 \). The simple effect of distractor type was no longer significant for the colour search session, \( F(2,30) = 2.48, p = .101, \eta_p^2 = .142 \), but remained significant for the motion search session, \( F(2,30) = 7.52, p = .002, \eta_p^2 = .334 \). Planned follow-up linear contrasts revealed that for the colour search session, TC distractors were associated with significantly larger N2pc amplitudes (M
= −1.08 µV, SE = 0.17 µV) than NTC or motion distractors, \( t(15) = 2.88, p = .011 \), that did not differ from each other (\( M = −0.33 \) µV, \( SE = 0.24 \) µV and \( M = −0.32 \) µV, \( SE = 0.26 \) µV respectively), \( t(15) = 0.01, p = .996 \). In contrast, for the motion search session, motion distractors were associated with significantly larger N2pc amplitudes (\( M = −1.33 \) µV, \( SE = 0.29 \) µV) than TC or NTC distractors, \( t(15) = 3.24, p = .006 \), that did not differ from each other (\( M = −0.05 \) µV, \( SE = 0.23 \) µV and \( M = 0.19 \) µV, \( SE = 0.21 \) µV respectively), \( t(15) = 0.74, p = .469 \). Thus, for both of the search tasks, distractors that possessed the current target feature evoked a larger N2pc than distractors that did not. These results are strikingly consistent with those from the main analysis, particularly considering the reduction in signal-to-noise ratio in these data due to the greatly reduced number of stimuli contributing to each waveform. This suggests that the effects of task set on distractor-related N2pc amplitudes reported here hold true for the subset of trials in which all distractors were accompanied by a target event.
To summarise, in Experiment 1 I found distractors evoked a larger N2pc component, and slowed responses to targets more, when they possessed a feature relevant to an observer’s current search task. These findings replicate and extend previous evidence for top-down modulation of attentional capture (e.g., Folk et al., 1992; Lien et al., 2008), demonstrating that the results observed previously
in static onset displays generalise to situations involving sustained monitoring of dynamic stimulus displays. Additional analyses indicated that the observed results could not be attributed to eye movements toward the distractor stimuli, and that the N2pc results were comparable regardless of whether the distractor events that elicited them appeared alone or were accompanied by a target.

3.2. Experiment 2

3.2.1. Introduction

In Experiment 2 I went on to test the possibility that selective attention and WM utilise common neural resources. Participants performed the same coloured bar search task from Experiment 1 concurrently with a digit rehearsal task adapted from Lavie and De Fockert (2005), designed to impose low or high load on observers’ WM resources. I reasoned that if selective attention and WM compete for common neural resources (e.g., Gazzaley & Nobre, 2012; Lavie et al., 2004), the influence of task set on attentional capture should be reduced under high WM load. I used the same two measures of attentional capture as in Experiment 1; the N2pc associated with the distractor stimuli, and the extent to which their presence interfered with responses to concurrent target events.

3.2.2. Method

Participants

Twenty-four staff and students (fourteen female, aged between 20 and 30 years) from The University of Queensland took part in Experiment 2. Data from three participants were excluded from all analyses due to EEG data recording errors.

Procedure

Figure 3-4 illustrates the key elements of the visual stimuli used in Experiment 2. The procedure was similar to that of Experiment 1, with the following exceptions. To impose a load on WM, participants were shown a series of five digits to hold in memory during the coloured bar search task. The digits could be either sequentially ordered (low WM load) or random (high WM load), with the constraints that zero was always the first digit, and that the other four digits were 1, 2, 3, and 4. The digits (RGB 150, 150, 150, presented in ‘Arial’ font, height = 1.2°) were presented at fixation for 1.5 s, followed by a 1.5 s blank screen prior to each stimulus stream. After each stimulus stream, which now lasted 16 s, a single probe digit was presented, and participants had to report the digit that appeared to the right of the probe in the digit series presented at the start of the
stream. To accommodate for the added factor of WM load while still maintaining an adequate number of epochs per cell for the N2pc analysis, I did not include the radial motion search task and associated stimuli from Experiment 1 in this experiment. Rather than varying the target colour between participants, I alternated the target colour within participants such that each participant searched for green bars during some streams and red bars during others. I did this to prevent the search task becoming highly automatised, as this might have reduced any potential interactive effects of task set and WM load (for discussion, see Carlisle, Arita, Pardo, & Woodman, 2011; Woodman et al., 2007).

Figure 3-4 Paradigm for Experiment 2. Prior to each stimulus stream participants were presented with a series of digits to hold in memory, that could either be sequentially ordered (‘01234’; low WM load) or random (as in the example above; high WM load). Participants then fixated a central plus sign and covertly monitored dynamic stimulus streams above and below fixation for groups of either red or green bars (varied across blocks of trials). Groups of red or green bars were also presented within dynamic stimulus streams to the left and right of fixation, and served as distractors. After each stimulus stream a single probe digit was presented (‘4’ in the example above), and participants had to report
the digit that appeared to the right of the probe in the digit series presented at the start of the stream (in this case, the correct response would be ‘2’).

Participants completed a single session involving 12 practice streams and then 12 blocks of 8 experimental streams. The target colour for the bar search task (green or red) alternated after each block. Half of the participants started with green as their first target colour, and the other half started with red. WM load (low or high) alternated every second block, also counterbalanced across participants. The visual feedback used in the practice streams of Experiment 1 was replaced by auditory feedback (correct responses were followed by a high-pitched beep; incorrect responses were followed by a low-pitched beep). The same auditory feedback was provided for the digit rehearsal task responses throughout the experiment. At the end of each block participants were informed of their average hit rate and RT for the coloured bar search task, and their accuracy on the digit rehearsal task.

Electroencephalography

Procedures for recording and analysing EEG data were identical to those of Experiment 1. An average of 5% of epochs per participant were automatically rejected for excessive noise artifacts. The remaining epochs were then averaged together separately for each combination of WM load (low, high) and distractor type (TC, NTC), and collapsed across distractor location. An average of 136 epochs contributed to each waveform for each of the 21 participants and each of the four conditions.

3.2.3. Results

Behaviour

Participants’ accuracy on the digit rehearsal task was significantly lower for the high WM load task ($M = 92.86\%$, $SE = 1.48\%$) relative to the low WM load task ($M = 97.22\%$, $SE = 0.82\%$), $t(20) = 3.86$, $p < .001$. These accuracy rates are very similar to those reported for the same task by Lavie and De Fockert (2005; Experiment 2). Figure 3-5 displays mean hit rates and RTs on the coloured bar search task for each combination of WM load (low, high) and distractor type (none, TC, NTC). The two behavioural measures were subjected to separate $2 \times 3$ within-subjects ANOVAs with factors of WM load and distractor type. Each participant was exposed to 48 target events for each of the six cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For hit rates (Figure 3-5a) there was no significant main effect of
WM load, $F(1,20) = 0.22, p = .643$, or distractor type, $F(2,40) = 1.51, p = .233$, and no interaction between the factors, $F(2,40) = 0.475, p = .625$.

![Graph](image1)

**Figure 3-5** Behavioural results for Experiment 2. (a) Hit rates. (b) Reaction times. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

For RTs (Figure 3-5b), there was a marginally significant main effect of WM load, $F(1,20) = 4.08, p = .057, \eta^2_p = .169$, such that responses on the coloured bar search task tended to be faster in the low WM load streams ($M = 638 \text{ ms}, SE = 3 \text{ ms}$) than in the high WM load streams ($M = 648 \text{ ms}, SE = 3 \text{ ms}$). There was also a significant main effect of distractor type, $F(2,40) = 16.04, p < .001, \eta^2_p = .445$, which was followed up by within-subjects $t$ tests with a Bonferroni corrected alpha of .017 (3 comparisons). Relative to the no distractor baseline ($M = 633 \text{ ms}, SE = 2 \text{ ms}$), RTs were significantly increased in the presence of both TC distractors ($M = 655 \text{ ms}, SE = 3 \text{ ms}$), $t(20) = 6.05, p < .001$, and NTC distractors ($M = 642 \text{ ms}, SE = 2 \text{ ms}$), $t(20) = 2.64, p = .016$. RTs were also significantly longer in the presence of TC relative to NTC distractors, $t(20) = 2.85, p = .010$. There was no interaction between WM load and distractor type, $F(2,40) = 0.56, p = .576$. As with my findings from Experiment 1, these behavioural results are consistent with the contingent capture hypothesis (Folk et al., 1992) that task-relevant distractors are more potent captors of attention than task-irrelevant distractors. Further, this effect was not reduced by the digit rehearsal WM load manipulation. This pattern of results differs from that reported by Lavie and De Fockert (2005), who found that the same manipulation of WM load increased the behavioural interference associated with task-irrelevant colour singletons.

**Electroencephalography**

Panels a – d of Figure 3-6 display the waveforms associated with each combination WM load (low, high), and distractor type (TC, NTC) at electrodes PO7/8, lateralised relative to distractor location. The mean N2pc amplitudes extracted from these waveforms are plotted in Figure 3-6e. Mean N2pc amplitude was significantly different from zero in each of the four conditions (all $p \leq .002$). Target-coloured distractors evoked larger N2pcs than NTC distractors, at both levels of WM load. A $2 \times 2$
within-subjects ANOVA with factors of search type and distractor type yielded a significant main effect of distractor type, $F(1,20) = 8.42, p = .009, \eta_p^2 = .296$, confirming that N2pc amplitudes were larger for TC distractors ($M = -1.31 \mu V, SE = 0.06 \mu V$) than for NTC distractors ($M = -0.94 \mu V, SE = 0.06 \mu V$). There was no significant main effect of WM load, $F(1,20) = 1.28, p = .271$, and no interaction between the factors, $F(1,20) = 0.30, p = .588$. As with the behavioural data, these results replicate my Experiment 1 findings of an effect of task set on the N2pc, but indicate no influence of the digit rehearsal WM load manipulation on this effect\[15\].

Figure 3-6 Event-related potential results for Experiment 2. (a – d) Grand average waveforms associated with the distractors at electrodes PO7/8 across the conditions of WM load and distractor type, separately for the contralateral and ipsilateral waveforms relative to distractor location. The shaded boxes indicate 200 – 280 ms post stimulus onset, the time window used for the N2pc analyses. The topographical map accompanying each panel is a spherical spline interpolation of the average amplitude difference between the contralateral and ipsilateral waveforms across this time.

\[15\] Visual inspection of Figure 3-6a – d indicates that the contralateralised difference associated with the distractors in this experiment may have occurred slightly earlier than in the other three experiments reported in this chapter. Repeating the N2pc analysis using a slightly earlier time window (180 – 260 ms post stimulus onset) yielded statistically identical results, suggesting that the earlier onset of the N2pc in this experiment had no effect on the analysis of mean N2pc amplitudes.
window. It should be interpreted as if the distractors had always been presented in the left distractor location. (e) Mean N2pc amplitude associated with the distractors across the conditions of WM load and distractor type. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

I conducted the same two additional analyses employed in Experiment 1 to investigate whether the observed N2pc effects could have resulted from eye movements rather than shifts of attention. The maximum deflection toward the distractor stimuli in the HEOG waveforms over the N2pc time window in any participant was 2.05 µV, within the standard threshold of ±3 µV used for rejecting participants due to excessive eye movements. Subjecting the HEOG data to the same 2 × 2 within-subjects ANOVA applied to the N2pc data yielded no effect of WM load or distractor type, and no interaction between the factors (all p ≥ .201).

To summarise, in Experiment 2 I replicated my observations from Experiment 1 that distractors evoked a larger N2pc component, and slowed responses to targets more, when they possessed the target feature value. Against my predictions, however, the WM load manipulation did not alter the effect of task relevance on either measure of attentional capture. Given that WM is widely held to consist of multiple related but dissociable components (Baddeley, 2003, 2012; Miyake et al., 2000), it is possible that the digit rehearsal task employed in Experiment 2 did not sufficiently tax the appropriate component of WM in relation to attentional capture.

3.3. Experiment 3

3.3.1. Introduction

In Experiment 3 I tested whether a different WM load manipulation, involving information-updating, could influence contingent attentional capture. Updating refers to the process of monitoring and evaluating incoming information for relevance to the current task(s) and then incorporating relevant new information into the information currently held in short-term memory (Morris & Jones, 1990). To vary the load on the updating component of WM, I had participants either perform the same coloured bar search task from Experiment 1 on its own, or perform it concurrently with a 2-back task (Chatham et al., 2011). For this task, participants monitored a stream of letters at fixation and kept a tally of the number of times a letter was repeated two positions apart within the stream. The letter stream was still present during the no WM load condition, but observers were instructed to ignore it. As before, I reasoned that if selective attention and WM compete for common neural resources, task set should have less of an effect on attentional capture under WM load.
One possible explanation for why I failed to replicate the observation by Lavie and De Fockert (2005) that WM load increases behavioural interference produced by a task-irrelevant distractor is that my task-irrelevant NTC distractors were inherently less salient than the task-irrelevant colour singletons used by Lavie and De Fockert. To test this, I introduced an additional distractor type in Experiment 3, with the intention of giving it the best possible chance of being a potent captor of attention. On the basis of previous research suggesting that high contrast, sudden onset stimuli are particularly salient (Theeuwes, 1991a; Yantis & Jonides, 1984, 1990, 1996) I selected an onset distractor, which involved one of the two lateralised bounding boxes being filled completely white. To further enhance the inherent salience of the onset distractor, I presented it very briefly (100 ms, as opposed to the 467 ms duration of the TC and NTC distractors).

3.3.2. Method

Participants

Twenty-four staff and students (ten female, aged between 19 and 31 years) from The University of Queensland took part in Experiment 3.

Procedure

Figure 3-7 illustrates the key elements of the visual stimuli used in Experiment 3. The procedure was similar to Experiment 1, with the following exceptions. Rather than a central plus sign, participants were asked to fixate a central stream of gray letters (RGB 127, 127, 127, presented in ‘Arial’ font, height = 1.2°, duration = 400 ms, SOA = 1200 ms). In the 2-back WM load condition, as well as performing the coloured bar search task, participants monitored for 2-back repetitions in the central letter stream (Chatham et al., 2011; Kirchner, 1958). There were zero, one, or two of the relevant repetitions in each 16 s stimulus stream. The repeated letters (if any) and the other letters within each stream were randomly selected without replacement from the English alphabet. The first letter of a repetition could not appear before the third letter of each stream, and if there were two repetitions in a stream, they had to be separated by at least one non-repeated letter. At the end of each stream the text “0, 1, or 2?” appeared on screen to prompt the participant to report how many of the relevant repetitions had been seen, by pressing one of three keys on the keyboard. There was no radial motion search session, and target colour was alternated within participants.
Figure 3-7 Paradigm for Experiment 3. A serial stream of letters replaced the central plus sign from Experiment 1. In the 2-back WM load condition, observers had to perform a dual 2-back task in addition to the original bar orientation discrimination task described previously. Target colour was varied between blocks. Observers could ignore the letter stream in the no WM load condition. I also added an onset distractor, during which one of the lateralised bounding boxes was briefly filled entirely in white (RGB 255, 255, 255).

Participants completed a single session involving six practice and 12 experimental blocks, with each block containing eight 16 s stimulus streams. The target colour for the bar search task alternated after each block, and WM load alternated every second block, both counterbalanced across participants. Correct responses to the target bars during the practice blocks were followed by a high-pitched beep, and incorrect responses were followed by a low-pitched beep. The same auditory feedback was also provided for the 2-back task responses throughout the experiment. At the end of each block participants were informed of their average hit rate and RT for the coloured bar search task, and their accuracy on the 2-back task (if applicable).
Electroencephalography

Procedures for recording and analysing EEG data were identical to those of Experiment 1. An average of 6% of epochs per participant were automatically rejected for excessive noise artifacts. The remaining epochs were then averaged together separately for each combination of WM load (no, 2-back) and distractor type (TC, NTC, onset), and collapsed across distractor location. An average of 135 epochs contributed to each waveform for each of the 24 participants and each of the six conditions.

3.3.3. Results

Behaviour

Mean accuracy on the 2-back task was 71%. Figure 3-8 displays mean hit rates and RTs on the coloured bar search task for each combination of WM load (no, 2-back), and distractor type (none, TC, NTC, onset). These two behavioural measures were subjected to separate 2 × 4 within-subjects ANOVAs with factors of WM load and distractor type. Each participant was exposed to 48 target events for each of the eight cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For hit rates (Figure 3-8a), there was no main effect of WM load, $F(1,23) = 0.86, p = .363$, no main effect of distractor type, $F(3,69) = 2.32, p = .083$, and no interaction between the factors, $F(3,69) = 1.24, p = .301$.

For RTs (Figure 3-8b), a significant main effect of WM load, $F(1,23) = 79.99, p < .001, \eta^2_p = .777$, indicated that RTs were longer overall while participants were concurrently performing the 2-back WM load task ($M = 710 \text{ ms}, SE = 16 \text{ ms}$) than when they were not performing a concurrent WM load task ($M = 647 \text{ ms}, SE = 15 \text{ ms}$). There was also a significant main effect of distractor type, $F(3,69) = 7.34, p < .001, \eta^2_p = .242$, that was followed up by within-subjects $t$ tests with a
Bonferroni corrected alpha of .008 (6 possible comparisons). Relative to the no distractor baseline ($M = 675$ ms, $SE = 15$ ms), RTs were significantly increased in the presence of TC distractors ($M = 688$ ms, $SE = 16$ ms), $t(23) = 3.09, p = .005$, unchanged in the presence of NTC distractors ($M = 679$ ms, $SE = 15$ ms), $t(23) = 1.68, p = .107$, and unchanged in the presence of onset distractors ($M = 672$ ms, $SE = 15$ ms), $t(23) = 0.69, p = .497$. There was no interaction between the factors, $F(3,69) = 1.03, p = .384$. Thus, unlike previous behavioural studies (e.g., Lavie & De Fockert, 2005), neither of my task-irrelevant distractors significantly impaired behavioural performance at either level of WM load. In fact, the introduction of a WM load had no effect on the behavioural interference produced by either task-relevant or irrelevant distractors.

**Electroencephalography**

Panels a–f of Figure 3-9 display the waveforms associated with each combination WM load (no, 2-back), and distractor type (TC, NTC, onset) at electrodes PO7/8, lateralised relative to distractor location. Mean N2pc amplitudes across the standard N2pc time window are plotted in Figure 3-9g. Visual inspection of the waveforms, topography insets, and mean N2pc amplitudes corresponding to onset distractor conditions indicates that the ERP activity associated with these stimuli during the selected N2pc time window differs markedly from that associated with the other distractor types. All other distractor conditions in all four experiments yielded a topographical map characterised by a concentration of negative voltage at posterior scalp electrodes, particularly contralateral to the visual stimulus location. This topographical distribution is clearly absent from the onset distractor conditions. Based on these observations, I elected to exclude the onset distractors from the N2pc analysis in this experiment. Mean N2pc amplitudes for the remaining four conditions were all significantly different from zero (all $p \leq .010$), and were subjected to a $2 \times 2$ within-subjects ANOVA with factors of WM load (no, 2-back) and distractor type (TC, NTC). A significant main effect of distractor type, $F(2,46) = 16.17, p < .001, \eta^2_p = .413$, was qualified by a significant interaction between the factors, $F(2,46) = 6.92, p = .002, \eta^2_p = .231$. For TC distractors, the N2pc was significantly larger under no WM load ($M = –1.43 \mu$V, $SE = 0.25 \mu$V) than under a 2-back WM load ($M = –0.74 \mu$V, $SE = 0.26 \mu$V), $t(23) = 3.49, p = .002$. In contrast, there was no effect of WM load on N2pc amplitude associated with the NTC distractors, $t(23) = 1.36, p = .187$, or onset distractors, $t(23) = 0.47, p = .641$. These results provide the first evidence that increasing WM load reduces the influence of task set on the N2pc.
Figure 3-9 Event-related potential results for Experiment 3. (a – f) Grand average waveforms associated with the distractors at electrodes PO7/8 across the conditions of WM load and distractor type, separately for the contralateral and ipsilateral waveforms relative to distractor location. The shaded boxes indicate 200 – 280 ms post stimulus onset, the time window used for the N2pc analyses. The topographical map accompanying each panel is a spherical spline interpolation of the average amplitude difference between the contralateral and ipsilateral waveforms across this time window. It should be interpreted as if the distractors had always been presented in the left distractor location. (g) Mean N2pc amplitude associated with the distractors across the conditions of WM load and distractor type. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

I conducted the same two additional analyses employed in Experiment 1 to investigate whether the observed N2pc effects could have resulted from eye movements rather than shifts of attention. The maximum deflection toward the distractor stimuli in the HEOG waveforms over the N2pc time window in any participant was 2.62 µV, within the standard threshold of ±3 µV used for rejecting
participants due to excessive eye movements. Subjecting the HEOG data to the same 2 × 2 within-subjects ANOVA applied to the N2pc data yielded no effect of WM load or distractor type, and no interaction between the factors (all \( p \geq .129 \)).

Although the onset distractors in the present experiment did not evoke a posterior contralateral negativity during the typical N2pc time window, they appear to have evoked a posterior contralateral negativity in the period leading up to the standard N2pc time window. This earlier contralateral negativity was entirely absent (perhaps even reversed) in the TC and NTC distractor conditions (see Figure 3-9e – f). This pattern of observations is strikingly similar to those observed in Experiment 1 (see Figure 3-2a – f), in which the latency of the posterior contralateral negativity appeared to have commenced earlier for the motion distractors, relative to the TC and NTC distractors. Figure 3-10 more clearly highlights these observations by reproducing the waveforms for the motion distractors from Experiment 1 (Figure 3-10a – b), and the onset distractors from Experiment 3 (Figure 3-10c – d). As indicated by the bordered hollow boxes, a posterior contralateral negativity appears to have commenced earlier than the shaded N2pc time window for the motion distractors, and earlier still for the onset distractors. These earlier contralateral negativities were affected by task set and WM load in the same fashion as the activity occurring in the standard N2pc time window: For Experiment 1, activity associated with the motion distractor was more negative during the motion search than during the colour search \( t(15) = 2.99, p = .009 \); and for Experiment 3, activity associated with the onset distractor did not differ in the presence of a WM load, \( t(23) = 1.06, p = .301 \).
Figure 3-10 Exploratory analysis of early contralateral negativity associated with salient distractors. The grand average waveforms associated with the motion distractors in Experiment 1 are re-plotted in (a) and (b), and those associated with the onset distractors in Experiment 3 are re-plotted in (c) and (d). The shaded boxes indicate 200 – 280 ms post stimulus onset, the time window used for the N2pc analyses. The bordered hollow boxes indicate time windows selected separately for each distractor to capture the evoked contralateral negativity (160 – 260 ms post stimulus onset for the motion distractor; 100 – 220 ms post stimulus onset for the onset distractor). The topographical map accompanying each panel is a spherical spline interpolation of the average amplitude difference between the contralateral and ipsilateral waveforms across the visually selected time window. It should be interpreted as if the distractors had always been presented in the left distractor location.

The early contralateral negativities associated with the salient motion (Experiment 1) and onset (Experiment 3) distractors fit with the widely held perspective that stimulus salience modulates early stages of processing (e.g., Luck, 2005). These effects also tie in nicely with previous findings that fast saccades made during visual search tasks are more likely than slow saccades to be directed toward salient distractors than toward a target object (van Zoest & Donk, 2005; Van Zoest, Donk, & Theeuwes, 2004; but see Wu & Remington, 2003). Similarly, fast manual localization responses are more likely than slow responses to be directed toward salient distractors than toward the target object (Hunt, von Muhlenen, & Kingstone, 2007). There is also electrophysiological evidence that salient task-irrelevant distractors occasionally evoke earlier contralateral negativities than less salient target objects (Hickey, van Zoest, & Theeuwes, 2010; but see McDonald, Green, Jannati, & Di Lollo, 2013 for an alternative perspective).

To summarise, in Experiment 3 I demonstrated once again that task-relevant distractors evoked a larger N2pc component, and slowed responses to targets more, than task-irrelevant distractors. In
line with my predictions, and unlike the WM load manipulation employed in Experiment 2, the effect of task set on N2pc amplitudes was reduced under high WM load. In contrast, the present WM load manipulation had no measurable effect on the pattern of behavioural interference associated with the distractors.

A caveat to the findings of this experiment is that the \( n \)-back WM load manipulation was confounded with single- versus dual-task performance. I chose this particular manipulation to maximise statistical power to detect an effect of WM load, in case my failure to observe any effect of WM load in Experiment 2 was due to a lack of power. As a consequence, however, the effect I did observe in Experiment 3 could be related to some aspect of performing an additional task unrelated to WM load. In the 2-back WM load condition, observers had to maintain an additional set of rules about target features and appropriate responses, and monitor an additional stream of visual stimuli. Competition over resources for any of these aspects of task performance could potentially explain the reduced effect of the coloured bar search task set on the N2pc in this condition.

3.4. Experiment 4

3.4.1. Introduction

In Experiment 4 I sought to test whether my Experiment 3 findings could be specifically attributed to WM load, or could instead have been due to some other aspect of single- versus dual-task performance. Rather than comparing single-task performance to dual-task performance, as I did in Experiment 3, I varied the WM load imposed by the letter monitoring task by having participants monitor for either 1-back (low WM load) or 2-back (high WM load) repetitions. In this way, participants performed both tasks under both levels of WM load, and only WM load itself varied between the two levels. An additional aim of Experiment 4 was to provide a replication of the unexpected dissociation I observed in Experiment 3 between my electrophysiological and behavioural measures of attentional capture.

3.4.2. Method

Participants

Sixteen staff and students (ten female, aged between 19 and 37 years) from The University of Queensland took part in Experiment 4.
Procedure

Figure 3-11 illustrates the key elements of the visual stimuli used in Experiment 4. The procedure was similar to that of Experiment 3, with the following exceptions. In the low WM load condition, participants kept a tally of the number of times a letter was repeated twice in a row in the central letter stream (1-back task). In the high WM load condition, participants kept a tally of the number of times a letter was repeated two positions apart within the central letter stream (2-back task). Both of these tasks were performed concurrently with the original bar orientation discrimination task from Experiment 1. Because of the ambiguity of the ERP results associated with the onset distractor in Experiment 3, I decided to remove this distractor type from Experiment 4. Participants completed a 30 minute training session to become proficient at the tasks prior to completing one experimental session. The experimental session consisted of four practice and 20 experimental blocks, with each block containing eight 16 s stimulus streams. The target colour for the bar search task alternated after each block, and WM load alternated every second block, both counterbalanced across participants.

Figure 3-11 Paradigm for Experiment 4. Observers performed a dual n-back task that placed either low (1-back) or high (2-back) demands on WM, as well as performing the original bar orientation discrimination task described previously. Target colour was varied between blocks.
Electroencephalography

Procedures for recording and analysing EEG data were identical to those of Experiment 1. An average of 5% of epochs per participant were automatically rejected for excessive noise artifacts. The remaining epochs were then averaged together separately for each combination of WM load (low, high) and distractor type (TC, NTC), and collapsed across distractor location. An average of 228 epochs contributed to each waveform for each of the 16 participants and each of the four conditions.

3.4.3. Results

Behaviour

Participants’ accuracy on the n-back task was significantly lower for the high WM load condition (2-back; \( M = 75.31\% \), \( SE = 3.55\% \)) than for the low WM load condition (1-back; \( M = 80.86\% \), \( SE = 2.43\% \)), \( t(15) = 2.81 \), \( p = .013 \). Figure 3-12 displays mean hit rates and RTs on the coloured bar search task for each combination of WM load (low, high), and distractor type (none, TC, NTC). These two behavioural measures were subjected to separate 2 × 3 within-subjects ANOVAs with factors of WM load and distractor type. Each participant was exposed to 80 target events for each of the six cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For hit rates (Figure 3-12a), a significant main effect of WM load, \( F(1,15) = 4.72 \), \( p = .046 \), \( \eta^2_p = .239 \), indicated that hit rates to the target-coloured bars were lower while participants were concurrently performing the high WM load task (\( M = 92.66\% \), \( SE = 1.11\% \)) than when they were concurrently performing the low WM load task (\( M = 93.72\% \), \( SE = 0.95\% \)). There was no main effect of distractor type, \( F(2,30) = 0.86 \), \( p = .434 \), and no interaction between the factors, \( F(2,30) = 1.31 \), \( \varepsilon = .71 \), \( p = .282 \).

![Figure 3-12](image-url) Behavioural results for Experiment 4. (a) Hit rates. (b) Reaction times. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).
For RTs (Figure 3-12b), a significant main effect of WM load, $F(1,15) = 45.89, p < .001, \eta^2_p = .754$, indicated that RTs were slower overall while participants were concurrently performing the high WM load task ($M = 665$ ms, $SE = 2$ ms) than when they were concurrently performing the low WM load task ($M = 648$ ms, $SE = 2$ ms). There was also a significant main effect of distractor type, $F(2,30) = 4.87, p = .015, \eta^2_p = .245$, that was followed up by within-subjects $t$ tests with a Bonferroni corrected alpha of .017 (3 comparisons). Relative to the no distractor baseline ($M = 651$ ms, $SE = 2$ ms), RTs were significantly increased in the presence of NTC distractors ($M = 661$ ms, $SE = 2$ ms), $t(15) = 3.92, p = .001$, and marginally increased in the presence of TC distractors ($M = 658$ ms, $SE = 2$ ms), $t(15) = 2.12, p = .052$. There was no significant difference in RTs between TC and NTC distractors, $t(15) = .76, p = .460$, and no interaction between the WM load and distractor type, $F(2,30) = 0.38, p = .689, \eta^2_p = .024$. Thus, in contrast to the previous three experiments and against the contingent capture theory (Folk et al., 1992), there was no apparent effect of task set on the behavioural interference associated with distractors. This unexpected difference will be discussed in Section 3.5.

**Electroencephalography**

Panels a – d of Figure 3-13 display the waveforms associated with each combination of WM load (low, high) and distractor type (TC, NTC) at electrodes PO7/8, lateralised relative to distractor location. The mean N2pc amplitudes extracted from these waveforms are plotted in Figure 3-13e. Mean N2pc amplitudes were significantly different from zero in the low WM load, TC distractor condition, $t(15) = 2.86, p = .012$, but were not statistically different from zero in the other three conditions (all $p \geq .158$). Mean N2pc amplitudes were subjected to a $2 \times 2$ within-subjects ANOVA with factors of search type and distractor type. There was a significant main effect of WM load, $F(1,15) = 5.07, p = .040, \eta^2_p = .252$, and a significant main effect of distractor type, $F(1,15) = 10.07, p = .006, \eta^2_p = .402$, but no interaction between the factors, $F(1,15) = 1.41, p = .253$. Based on my observations in Experiment 3, however, I had a priori expectations that there would be an effect of task set under low but not high WM load, and these expectations appear to be supported by the mean amplitudes presented in Figure 3-13e. For these reasons, I elected to conduct planned within-subjects $t$ tests on the effect of distractor type, separately for each level of WM load. Under low WM load, TC distractors were associated with significantly larger N2pc amplitudes ($M = -0.64 \mu V, SE = 0.16 \mu V$) than NTC distractors ($M = -0.33 \mu V, SE = 0.11 \mu V$), $t(15) = 3.39, p = .004$. In contrast, under high WM load, N2pc amplitudes did not differ between TC and NTC distractors ($M = -0.39 \mu V, SE = 0.16 \mu V$ and $M = -0.26 \mu V, SE = 0.16 \mu V$ respectively), $t(15) = 1.24, p = .234$. 

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Thus, as in Experiment 3, there was a statistically significant effect of task set on the N2pc under low- but not high-WM load.

Figure 3-13 Event-related potential results for Experiment 4. (a – d) Grand average waveforms associated with the distractors at electrodes PO7/8 across the conditions of WM load and distractor type, separately for the contralateral and ipsilateral waveforms relative to distractor location. The shaded boxes indicate 200 – 280 ms post stimulus onset, the time window used for the N2pc analyses. The topographical map accompanying each panel is a spherical spline interpolation of the average amplitude difference between the contralateral and ipsilateral waveforms across this time window. It should be interpreted as if the distractors had always been presented in the left distractor location. (e) Mean N2pc amplitude associated with the distractors across the conditions of WM load and distractor type. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

I conducted the same two additional analyses employed in Experiment 1 to investigate whether the observed N2pc effects could have resulted from eye movements rather than shifts of attention. The maximum deflection toward the distractor stimuli in the HEOG waveforms over the N2pc time window in any participant was 1.70 µV, within the standard threshold of ±3 µV used for rejecting participants due to excessive eye movements. Subjecting the HEOG data to the same 2 × 2 within-
subjects ANOVA applied to the N2pc data yielded no effect of WM load or distractor type, and no interaction between the factors (all $p \geq .156$).

To summarise, in Experiment 4 I replicated my observation from Experiment 3 that a 2-back WM load manipulation removed the effect of task set on the N2pc associated with distractors. Crucially, this effect was still apparent without the single- versus dual-task confound present in Experiment 3. This indicates that the observed reduction in the N2pc to task-relevant (TC) distractors is specifically related to WM load, and not to having to perform two tasks at the same time. There was no evidence for an effect of distractor task-relevance on RTs in Experiment 4. This is surprising given that I demonstrated an effect of task set on RTs in the other three experiments using essentially identical distractors, and also given the consistent effect of task set on the N2pc across all four experiments. Consistent with my earlier experiments, however, the pattern of behavioural interference observed under low WM load did not change under high WM load.

3.5. Discussion

Several theories of attentional control (e.g., Lavie et al., 2004) assert that maintaining effective top-down control settings involves similar neural resources to other cognitive control functions, such as maintaining and updating information in WM. One prediction that arises from this assertion is that introducing a WM load should impair the ability to implement a top-down set for objects with task-relevant features. I tested this prediction by examining whether placing demands on WM reduced the extent to which attention was preferentially captured by task-relevant distractors (the contingent capture effect; Folk et al., 1992). Participants searched for target objects defined by particular features (e.g., red bars) while distractors that either possessed or did not possess the target feature were presented at irrelevant, lateralised locations.

In three of the four experiments reported here, behavioural responses to the target stimuli were slowed by task-relevant distractors (e.g., red distractors when observers were looking for red targets) more than by task-irrelevant distractors (e.g., green distractors when observers were looking for red targets). Taken together, these behavioural results are consistent with the contingent capture theory that stimuli are more likely to capture attention if they possess features relevant to an observer’s current task (Folk & Remington, 2010; Folk et al., 1992). As with previous behavioural findings, the RT results I observed can also arguably be explained by the salience-driven selection and/ or rapid disengagement theories (Theeuwes, 1992, 2010). Proponents of these theories argue that the initial capture of attention is unaffected by task set, and that the effect of task set on RTs
arises because of differences in the speed with which attention can be disengaged from different distractors. However, the N2pc results observed here are also consistent with contingent capture: In all four experiments, task-relevant distractors evoked a larger N2pc than task-irrelevant distractors (in the absence of a concurrent high WM load). Unlike the behavioural results, these findings cannot readily be explained in terms of salience-driven selection and/or rapid disengagement theories, which holds that initial attentional capture is unaffected by task set. Given that the N2pc is widely taken as an index of spatial attentional selection (Eimer & Kiss, 2010a; Luck & Hillyard, 1994), if the initial capture of attention was indeed unaffected by task set, I would have expected no difference in N2pc amplitudes between task-relevant and task-irrelevant distractors.

Imposing demands on WM via a concurrent n-back task (Experiments 3 and 4) reduced the effect of task set on the distractor-evoked N2pc. Interestingly, this reduced effect of task set was driven by a selective reduction in the N2pc associated with task-relevant distractors, with no change apparent in the N2pc associated with task-irrelevant distractors. These observations dovetail nicely with the findings of Brisson et al. (2009), who found that a different manipulation of cognitive load had a similar effect on the N2pc as was observed here. In this previous study, the availability of cognitive resources was manipulated by presenting lateralised coloured distractors during or outside the PRP. In line with my findings, they found increasing cognitive load reduced the N2pc associated with task-relevant distractors, but had no effect on the N2pc associated with task-irrelevant distractors. The reduced effect of task set on the distractor-evoked N2pc under high WM load was not apparent, however, in participants’ behavioural data. I will discuss this dissociation in detail later.

My observation that taxing WM via an n-back task reduced the effect of task set on the N2pc associated with task-relevant distractors lends further weight to the emerging perspective that attention and WM are functionally and anatomically linked (Baddeley, 2012; Bengson & Mangun, 2011). Various theories of attention propose the existence of an ‘amodal’ central control network located within the prefrontal and parietal cortices, responsible for sending biasing signals to sensory neurons representing a specific spatial location, stimulus modality, or feature value/dimension (e.g., Desimone & Duncan, 1995; Petersen & Posner, 2012). Gazzaley and Nobre (2012) have proposed that the same central control network plays a similar role in WM, biasing lower-order sensory and motor areas toward whatever information the individual is currently trying to encode, maintain, update, or retrieve. According to this view, the n-back task recruited a frontal-parietal central control network, compromising the ability of this network to simultaneously bias activity within early visual cortices toward the colour relevant to the bar search task.
In contrast to the n-back task employed in Experiments 3 and 4, imposing demands on WM using a digit rehearsal task (Experiment 2) did not change the effect of task set on my behavioural or electrophysiological indices of attentional capture. That an n-back task but not a digit rehearsal task reduced the effect of task set on the distractor-evoked N2pc suggests that the effect of WM load on contingent capture may be specific to WM tasks that require both the maintenance and updating of information, and not just information maintenance on its own. A number of studies have indicated that different WM load manipulations can have different effects on different aspects of selective attention (e.g., S. Y. Kim et al., 2005; Konstantinou & Lavie, 2013). The present findings suggest that WM manipulations only influence contingent capture if they involve information-updating. This represents a novel extension of the general notion that WM load cannot be considered a unitary concept, and should be kept in mind during future investigations.

The absence of any effect of digit rehearsal on behaviour stands in contrast to previous findings that this kind of WM load manipulation increased the extent to which task-irrelevant distractors impaired target responses (Lavie & De Fockert, 2005). One factor that may have contributed to the different patterns of results is whether distractors appeared at a potentially task-relevant location. In the study by Lavie and De Fockert (2005), distractors always appeared at a location that could potentially contain the target item. In contrast, in my experiments distractors always appeared at a location observers knew would never contain a target. The same digit rehearsal task that impaired observers’ ability to suppress behavioural interference from distractors at task-relevant locations in Lavie and De Fockert’s study had no effect on the interference associated with distractors at task-irrelevant locations in my study. Perhaps location-specific filtering mechanisms are employed at locations known to be task-irrelevant, and it may be that these spatial filtering mechanisms are not susceptible to the influence of WM load. In other words, WM load may have different and interacting effects on attentional capture depending on whether both features and locations are relevant to an observer’s task. It would be useful for future research to test this possibility by factorially manipulating WM load and distractor task-relevance in terms of both features and locations.

Another difference between the present work and that of Lavie and De Fockert (2005) is that in the latter, observers were given a new set of digits to remember before every single distractor presentation. Such a design was not feasible in the present study, because doing so would have made it impractical to present the distractors enough times to reduce the electrophysiological signal-to-noise ratio to a reasonable level for the N2pc analyses. Instead, my participants were exposed to 16 s of stimulus streams containing multiple target and distractor events after each new set of digits.
It is possible that the digit rehearsal task only moderates the effect of task set on behaviour for a limited time after the digits are presented. For example, the effect may only be present while the digits are being encoded into memory, and not once they have been encoded and are simply being maintained. Insufficient trial numbers prevent us from testing this possibility with my current datasets, but this would be a worthwhile avenue for future research.

3.5.1. **Dissociations between electrophysiology and behaviour**

Across experiments I observed two noteworthy and unexpected dissociations between the N2pc and behaviour. First, although the $n$-back task reduced the effect of task set on the N2pc, it did not alter the effect of distractors on target responses. In both Experiments 3 and 4, increasing WM load via the $n$-back task slowed observers’ target responses in general (evidenced by a main effect of WM load), but did not change the relative extent of behavioural interference associated with the different distractor types. This same dissociation between electrophysiology and behaviour observed here was also reported by Brisson et al. (2009) using a very different manipulation of cognitive load. In both my study and theirs, increasing cognitive load reduced the effect of task set on the distractor-related N2pc, but did not change the effect of task set on behavioural responses to a competing target item. Dissociations between behaviour and the N2pc have also been observed in other contexts (e.g., Töllner et al., 2008, Woodman, 2010). These dissociations are difficult to reconcile with the popular view that the N2pc is a direct measure of the extent to which a stimulus has captured finite attentional resources to its location at the direct expense of all other locations (e.g., Woodman & Luck, 2003). If this were the case, any change in the N2pc should change the extent to which a stimulus compromises an observers’ ability to process, and ultimately respond to, a target item also competing for attention. Such a dissociation could possibly be explained by arguing that attention shifts from the distractor back to the target in the time interval between the peak of the N2pc and the selection and execution of the observer’s behavioural response. There is, however, other evidence that the N2pc might not reflect a singular and finite locus of spatial attention. Eimer and Grubert (2014) found that the N2pc associated with a lateralised target item was unaffected by the temporal proximity of a second target item on the vertical midline, even when the asynchrony between the two targets was only 10 ms.

A second dissociation I observed between electrophysiology and behaviour was that the presence (versus absence) of an N2pc could not reliably predict whether distractors would go on to interfere with target responses. Task-irrelevant distractors evoked a statistically reliable N2pc in Experiments 1, 2, and 3, but not in Experiment 4 (although the trend was always in the appropriate direction). In
contrast, the same task-irrelevant distractors only slowed target responses in Experiments 2 and 4; they failed to have any effect on target responses in Experiments 1 and 3. As with the dissociation discussed above, this pattern of results does not fit with the view that the N2pc directly indicates the extent to which a stimulus has captured finite attentional resources to its location. If this were true, any stimulus that evokes an N2pc should compromise an observers’ ability to process and respond to competing target items. One point to note here is that the distractor events used to evoke the N2pc in these experiments were not perfectly balanced for physical salience across the horizontal midline. Although the location opposite a current distractor always contained a dynamic field of moving dots, the dots were smaller than the bars that made up the distractor events, and lacked their sudden changes in shape and colour. This may explain why I still found an N2pc to task-irrelevant distractors where other studies (e.g., Brisson, Leblanc, & Jolicoeur, 2009; Eimer et al., 2009; Lien et al., 2010) did not. Nonetheless, that distractors didn’t always slow observers’ responses to target items, even if they were more salient than the target item (e.g., the onset distractors in Experiment 3), and even if they slowed target responses under other task conditions (e.g., red distractors when observers were looking for red versus green targets), compellingly supports the notion that physical salience doesn’t always drive behaviour (Folk & Remington, 2010; Folk et al., 1992). I argue that the dissociations described above have potentially far-reaching implications for how the N2pc is interpreted in studies of attention. It may be worth re-evaluating the simple view that any effect at the level of the N2pc reflects an allocation of attention that will be directly reflected in a similar effect on behavioural measures of attentional capture. Rather than seeing dissociations between electrophysiology and behaviour as an inconvenience, or arguing for the superiority of one measure or another, it is worth attempting to understand and investigate what such dissociations might be telling us about attention, beginning with the findings of the current study. I found that WM load reduced the effect of task set on the distractor-related N2pc but did not go on to have a similar effect on behaviour. One possible explanation for this is that the perceptual stages of processing reflected in the N2pc occur before an information bottleneck, perhaps akin to the bottleneck implicated in capacity limitations reflected by the attentional blink, visual short-term memory, and the PRP (Marois & Ivanoff, 2005). It may be that effects apparent at early processing stages indexed by the N2pc only go on to influence later processing stages under certain conditions—such as when adequate executive control resources are available. I speculate that allocating frontal-parietal control resources to the n-back task not only compromised the ability of this network to simultaneously bias activity in early visual cortices toward task-relevant features, but also compromised the transfer of this perceptual information on to later stages of processing.

16 Note that this does not necessarily imply that the n-back task should have completely removed any effect of task set on behaviour. It is entirely plausible that contingent capture is the product of biases toward task-relevant information at
3.5.2. Summary and conclusions

I replicated previous behavioural and electrophysiological evidence for contingent capture (e.g., Folk et al., 1992; Lien et al., 2008) by demonstrating that (a) responses to target items are slowed most by the presence of distractors that possess a task-relevant feature, and (b) task-relevant distractors evoke a larger N2pc component than task-irrelevant distractors. An n-back WM load manipulation requiring information maintenance and updating reduced the N2pc associated with task-relevant distractors, removing the effect of task set on the N2pc. These findings are consistent with the notion that WM and selective attention compete for common neural resources (Lavie et al., 2004). A different, digit rehearsal, WM load manipulation requiring information maintenance only had no effect on the distractor-evoked N2pc, suggesting that not all types of WM load have the same effect on attentional capture. The reduced effect of task set I observed on the N2pc under high n-back WM load was not apparent in behavioural responses to target items. This dissociation between the N2pc and behavioural indices of attention appears robust; it was apparent in two of the present experiments, and also in a very different previous study (Brisson et al., 2009). I argue that these dissociations compel us to re-evaluate the common view that the N2pc and behavioural indices of attention should always tell us exactly the same story. Further, investigating such dissociations could open up fruitful new avenues to furthering our understanding of the complexities and subtleties of attention. Applying this perspective to the current findings led me to speculate a novel explanation for why WM load reduced the effect of task set on the N2pc, but did not have a similar impact on behaviour.

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multiple stages of processing, not just the early stages reflected by the N2pc. As such, my speculation is consistent with the fact that I still observed an effect of task set on behaviour under high n-back load in Experiment 3.
Chapter 4. Interactive effects of task set and working memory load on early sensory processing
4.1. Introduction

In Chapter 3 I found that top-down control settings (e.g., searching for green objects) can influence stimulus processing at the level of the N2pc, and that this influence is reduced under conditions of high information-updating WM load. Previous research has indicated that searching for objects with specific features can influence even earlier stages of processing than those reflected by the N2pc. For example, Zhang and Luck (2009) presented observers with overlapping fields of red and green dots to either the left or right of fixation. Occasionally the dots in one colour would briefly dim – a target event – and observers were tasked with monitoring for target events in one of the coloured-dot fields. Irrelevant red or green “probe” dot fields were randomly presented in the opposite (unattended) visual field, and early visual ERPs evoked by these probes were compared between the attended and ignored colour. Relative to ignored-colour probes, attended-colour probes evoked a larger P1, a very early visual ERP component beginning less than 100 ms after stimulus onset (see also Moher et al., 2014). Many other studies have also found modulations of early visual ERP components by feature-based attention; not only by attention to a specific colour (Hillyard & Münte, 1984; Hopf et al., 2004), but also by attention to other features including motion direction (Hillyard & Anllo-Vento, 1998) and line orientation (Akyürek & Schubö, 2013; Bondarenko et al., 2012). Further evidence that feature-based attention affects very early stages of sensory processing has come from monkey studies using invasive electrophysiological recording, (e.g., Bichot et al., 2005; Treue & Martinez Trujillo, 1999; see Chapter 1 for details). There is even fMRI evidence in humans that attending to objects with a specific colour or motion direction can modulate processing in the pulvinar nuclei and lateral geniculate nucleus, presumably prior to the signal even arriving in the cortex (K. A. Schneider, 2011). Early effects of feature-based attention are apparent both within the current focus of spatial attention and also at unattended visual field locations (Maunsell & Treue, 2006).

Many researchers have proposed that the effects of feature-based attention on activity in sensory cortices are imposed by regions of prefrontal and parietal cortices (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Haenny & Schiller, 1988). This perspective fits well with anatomical evidence for extensive bidirectional connections between prefrontal and parietal cortices and most key regions of early visual cortex (Blatt, Andersen, & Stoner, 1990; Borra et al., 2008; Schall et al., 1995; Seltzer & Pandya, 1980). Functional evidence for prefrontal involvement in feature-based attention has come from invasive recording studies in monkeys. Zhou and Desimone (2011) had monkeys search through an array for target items while they recorded from neurons in both V4 and the FEF, an area of prefrontal cortex previously implicated in guiding spatially selective attention.
(Gregoriou, Gotts, Zhou, & Desimone, 2009; Moore & Armstrong, 2003). Neurons in both areas responded more strongly to the presence of objects with target features in their receptive fields. Further support for the notion that feature-based attention arises via frontal and parietal influences on early visual areas comes from fMRI studies in humans. For example, Serences et al. (2005) had observers monitor for letters of a particular colour at fixation. Peripheral distractor letters that matched the target colour evoked a larger BOLD response in extrastriate visual cortex, and also in a network of frontal and parietal brain regions including the FEF, IPS, TPJ, and VFC (see also Egner et al., 2008; Giesbrecht et al., 2003; Greenberg et al., 2010). There is now also direct causal evidence that parietal cortex is involved in the feature-based control of sensory processing. Schenkluhn et al. (2008) found that TMS over the IPS impaired participants’ perceptual sensitivity for briefly presented targets defined by a particular colour.

The same frontal and parietal regions implicated in feature-based attention have also been implicated in the control of spatial attention (Corbetta & Shulman, 2002; Giesbrecht et al., 2003; Slagter et al., 2007; Vandenberghhe et al., 2001), which suggests that this network may be responsible for many aspects of top-down attentional control. Many theoretical models also argue that the same or a very similar network is involved in WM (Awh et al., 2006; Baddeley, 2003; Chun, 2011; Conway et al., 2001; Desimone & Duncan, 1995; Lavie et al., 2004; E. K. Miller & Cohen, 2001). In line with this argument, numerous fMRI studies have found substantial overlap in activity between spatial attention and WM tasks (Corbetta et al., 2002; Gazzaley & Nobre, 2012; LaBar et al., 1999; Smith & Jonides, 1999). There is also good behavioural evidence for a functional link between WM and attentional control. Taxing WM has also been found to increase behavioural interference associated with distractor objects in a variety of visual search tasks (Boot et al., 2005; De Fockert et al., 2001; Lavie & De Fockert, 2005, 2006; Olivers et al., 2006). Studies using EEG have extended on these studies by demonstrating that, like feature-based attention, taxing WM can affect very early stages of distractor stimulus processing (Cocchi et al., 2011; Rose et al., 2005). Invasive recording studies in monkeys suggest that holding a specific object in memory enhances sensory responses to unattended distractors that share features with the remembered object as early as V4 (Hayden & Gallant, 2013).

As discussed previously, if feature-based attention and WM compete for shared top-down control resources, our ability to selectively attend to objects with task-relevant features should be compromised under high WM load. In the present experiment I set out to test whether the influence of feature-based attention on early sensory processing is compromised under high WM load. Following Zhang and Luck (2009), I took the P1 component as a measure of early sensory
processing, and I manipulated feature-based attention using the same coloured dot-monitoring task they used. To manipulate WM load, I introduced a dual-task element to the previous paradigm by inserting the same n-back letter task I used to manipulate WM load in Chapter 3 (Experiments 3 and 4). I had two predictions: First, that I would replicate Zhang and Luck’s finding that attended-colour probes evoke a larger P1 than ignored-colour probes, in the absence of any concurrent WM load. Second, in line with the findings described in Chapter 3, I predicted that any effect of feature-based attention on the P1 would be reduced under high WM load.

4.2. Method

4.2.1. Participants

Twenty-four staff and students (fifteen female, aged between 18 and 42 years) from The University of Queensland took part in this experiment. All participants reported normal or corrected-to-normal vision, and were screened for problems with colour vision using the Ishihara test for colour blindness. All procedures were approved by The University of Queensland Ethics Committee. Participants were financially reimbursed at a rate of AU$15 per hour.

4.2.2. Stimuli and apparatus

Visual stimuli were presented against a black background on an LCD monitor at a screen resolution of 1280 × 1024 pixels and a refresh rate of 60 Hz. Participants were seated at a viewing distance of 60 cm from the monitor, maintained using a chin rest. Stimulus presentation and response recording were controlled using Cogent software (Cogent 2000 toolbox: FIL, ICN, and Wellcome Department of Imaging Neuroscience) in Matlab version 7.13 (www.mathworks.com), running on a desktop computer.

4.2.3. Procedure

Figure 4-1 illustrates the key elements of the visual stimuli used in this experiment. The coloured-dot monitoring task was identical to the one used by Zhang and Luck (2009). At the start of each trial, a visual cue was presented at fixation (“<” or “>”), which informed the observer to covertly attend to either the left or right side of the screen. At the start of each half of the experiment, participants were instructed to monitor either the red or the green dots in the attended location. After a blank delay of 500 ms, overlapping fields of 50 red and 50 green dots were presented on the cued side of the screen. Dots were 0.2° wide and high, and were located within an invisible bounding circle 4° in diameter, centred 2.6° above and 8° to the left or right of fixation. Half of the
dots of each colour changed to a random new location within the bounding circle every 100 ms. Observers had to press a button every time they detected a transient (500 ms) decrease in luminance in the field of attended-colour dots in the attended location, which happened between two and five times per trial. Each trial lasted for 15 s. The ignored-colour dots in the attended location underwent the same number of transient luminance decrements as the attended-colour dots on each trial. The timings of the luminance decrements for the red dots were completely independent of the timings of the luminance decrements for the green dots. A task-irrelevant field of 50 homogeneously coloured red or green “probe” dots was presented for 100 ms in the contralateral (unattended) visual field 24 times per trial. These probe-dot fields were red or green with equal probability, and were the stimuli of interest for the EEG analyses. There was a minimum SOA of 400 ms between consecutive probes, and their timings were completely independent of the luminance decrements for the dot fields in the attended visual field.
Figure 4-1 Key elements of the visual stimuli used in this experiment. Continuous streams of overlapping green and red dots randomly moving within an invisible circle were presented either left or right of fixation (left in the example above). Observers covertly monitored for occasional luminance decrements in one of the colours (the green dots have dimmed in the second image above). Red or green “probe” dots were occasionally presented in the unattended visual hemifield, as in the green dots to the right of fixation in the third image above. In the no WM load condition, the central fixation point was a static plus sign. In the low and high WM load conditions, the plus sign was replaced by a letter stream (as in the figure above), and observers concurrently monitored a central stream of letters for 1- or 2-back repetitions.

There were three WM load conditions, undertaken in separate blocks of trials. In the no WM load condition, participants fixated on a central grey plus sign, and performed the coloured dots task on its own. In the low and high WM load conditions I replaced the central plus sign with a stream of grey letters (presented in ‘Arial’ font, height = 1.2°, duration = 400 ms, SOA = 1200 ms). In addition to performing the coloured dots task, participants monitored for either 1-back (low WM load) or 2-back (high WM load) repetitions in the central letter stream (Chatham et al., 2011; Kirchner, 1958). There were zero, one, or two of the relevant letter repetitions in each trial. The repeated letters (if any) and the other letters within each stream were randomly selected without replacement from the English alphabet. The first letter of a repetition could not appear before the
third letter of each stream, and if there were two repetitions in a stream, they had to be separated by at least one non-repeated letter. At the end of each stream, the text “0, 1, or 2?” appeared on screen to prompt the participant to report how many of the relevant repetitions had been seen in that stream, by pressing one of three keys on the keyboard.

Participants completed four practice trials for each of the three WM load conditions while the experimenters were setting up the EEG recording system. They then completed 12 experimental blocks, each containing 12 trials. The target colour for the coloured dots task (green or red) switched half way through the experiment, with the order counterbalanced across participants. Working memory load (no, low, or high) alternated after each block, also counterbalanced across participants. For both tasks, correct responses in the coloured dots task were followed by a high-pitched beep, and incorrect responses were followed by a low-pitched beep. At the end of each block, participants were informed of their average hit rate and RT for the bar search task for that block, and their average hit rate for the n-back task. An entire session per participant lasted approximately 1.5 hours.

4.2.4. Electroencephalography

Continuous electroencephalogram (EEG) data were recorded using a BioSemi Active Two system (BioSemi, Amsterdam, Netherlands), with the same recording parameters used in my previous studies (see Section 3.1.2).

Offline EEG data analysis was performed using BESA (6.0; MEGIS Software GmbH, Gräfelfing, Germany) and a purpose-built Matlab script. The data for the scalp electrodes were re-referenced to the average of all 64 scalp electrodes, and subjected to 0.1 Hz high-pass and 40 Hz low-pass digital filters. Noisy channels, identified by visual inspection of the data, were replaced by a spherical spline interpolation of the voltages recorded at all other scalp electrodes (a maximum of 5 per participant). The data were then segmented into epochs from 100 ms before to 400 ms after the onset of each probe event, with the average voltage in the 100 ms pre-stimulus interval serving as a baseline. Epochs in which the difference between the maximum and minimum voltage exceeded 120 µV at any channel were automatically rejected to remove epochs contaminated by blinks, eye movements and other artifacts. An average of 6.5% of epochs were rejected for violating this criterion. The remaining epochs were then averaged together, separately for each combination of WM load (no, low, high) probe colour (attended, ignored), and probe location (left, right). For the statistical analyses, data were collapsed across the two probe locations by creating separate
averages for contralateral and ipsilateral electrodes, relative to the probe location. An average of 538 epochs contributed to each waveform for each of the 24 participants and each of the 6 conditions.

4.3. Results

All statistical tests were conducted with a two-tailed alpha level of .05. Mauchly’s Test of Sphericity was applied to all within-subjects F tests. Greenhouse-Geisser epsilon adjustments were made to degrees of freedom for these F tests wherever the assumption of sphericity was untenable. Unadjusted degrees of freedom are reported for all F tests.

For my analysis of the P1 component, I averaged together the waveforms from electrodes P7/8 and P9/10, the two pairs of electrodes closest to those used by W. W. Zhang and Luck (2009) in their P1 analysis. It was not possible to use exactly the same electrodes because the 15 electrode locations used by Zhang & Luck did not all correspond to one of the international standard 10–10 system electrode locations I used. Figure 4-2a displays the waveforms associated with the two probe types, with each level of WM load on a separate set of axes. Mean P1 amplitudes were calculated from 80 – 130 ms after stimulus onset (the same time window used by W. W. Zhang & Luck, 2009), and are plotted in Figure 4-2b. These amplitudes were subjected to a $3 \times 2$ within-subjects ANOVA with factors of WM load and probe colour. There was no significant main effect of WM load, $F(2,46) = 2.31, \epsilon = .74, p = .127$, or probe colour, $F(1,23) = 0.50, p = .486$, and no significant interaction between the factors, $F(2,46) = 0.043, p = .958$. Planned follow-ups found no significant simple effect of probe colour at any level of WM load (no load, $t(23) = 0.21, p = .836$; low load, $t(23) = 0.70, p = .493$; high load, $t(23) = 0.68, p = .503$). The same pattern of results was observed when the two pairs of electrodes were analysed separately.
Figure 4-2 Event-related potential results for the P1 component. (a) Grand average waveforms associated with the probes at electrodes P7/P8/P9/P10 across the three WM load conditions, separately for the attended and ignored colour probes. The grey shaded area indicates 80 – 130 ms post stimulus onset, the time window used for the P1 analysis. To allow easier visual comparison with the waveforms reported by Zhang & Luck (2009) positive voltages are plotted upwards in these plots. (b) Mean P1 amplitudes for each condition. Error bars represent within-subjects standard errors of the means (Cousineau, 2005).

To more thoroughly explore the possible influences of task set and WM load on early stages of visual processing, I analysed the first five early visual ERP peaks described by Di Russo, Martínez, Sereno, Pitzalis, and Hillyard (2002), who used a visual stimulus of similar size and location to the probe stimuli used in the present study. These were: C1, taken as the mean amplitude 80 – 110 ms post stimulus onset at electrode POz; P1 contralateral, taken as the mean amplitude 80 – 110 ms at electrodes P9/10 contralateral to the probe location; P1 ipsilateral, taken as the mean amplitude 140 – 180 ms post stimulus onset at electrodes P7/8 ipsilateral to the probe location; N155, taken as the mean amplitude 140 – 180 ms post stimulus onset at electrodes C1/2 contralateral to the probe location; and N180, taken as the mean amplitude 160 – 200 ms post stimulus onset at electrodes P5/6 contralateral to the probe location. I subjected these five components to the same within-subjects ANOVA used in the main P1 analysis, with factors of WM load and probe colour. For the sake of brevity, I will not report specific results of all of these analyses, except to say that there were no significant main effects or interactions, all $p >= .141$. 

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Figures 4-4, 4-5, and 4-6 give a visual impression of how similar the activity associated with the attended and ignored colour probes was. They present the grand average waveforms at each of the 64 recorded scalp electrodes, with each level of WM load represented in a separate figure. The five earliest visual ERP peaks discussed in the previous paragraph are labeled in each figure. Waveforms are presented separately for left (upper panel) and right (lower panel) probes, because the topographical distribution of these early visual ERP peaks depends on the visual stimulus location. Notice that in most axes it is difficult to visually discriminate between the attended and ignored colour probe waveforms, due to the high degree of similarity between them.
Figure 4-3 Attended- and ignored-colour probe waveforms across all electrodes in the no WM load condition. Waveforms for probes presented on the left are contained in the upper panel, and waveforms for probes presented on the right are in the lower panel.
Figure 4–4 Attended- and ignored-colour probe waveforms across all electrodes in the low WM load condition.
Waveforms for probes presented on the left are contained in the upper panel, and waveforms for probes presented on the right are in the lower panel.
Figure 4-5 Attended- and ignored-colour probe waveforms across all electrodes in the high WM load condition. Waveforms for probes presented on the left are contained in the upper panel, and waveforms for probes presented on the right are in the lower panel.
4.4. Discussion

In the present experiment I further tested the notion that feature-based attention and WM compete for shared top-down control resources. Specifically, I examined whether the enhancement of early visual ERPs evoked by objects with task-relevant features is reduced under WM load. Unexpectedly, unlike the previous study by Zhang and Luck (2009) whose paradigm I used, I found no effect of feature-based attention on the P1 component, at any level of WM load.

It is worth noting that, as is the case in the present study, W. W. Zhang and Luck (2009) did not report any effect of feature-based attention on components later than the P1. Nor, for that matter, did the only subsequently published study that has used their paradigm (Moher et al., 2014). This stands in stark contrast to the findings of other ERP investigations of feature-based attention that have used different paradigms. For example, Hillyard and Münte (1984) found monitoring for objects of a specific colour enhanced the early visual ERP associated with target-coloured objects across a series of peaks, starting around 100 ms post stimulus onset but continuing out to around 500 ms post stimulus onset (see also Anllo-Vento & Hillyard, 1996; Eimer, 1997; Hillyard & Anllo-Vento, 1998; Kopp, Tabeling, Moschner, & Wessel, 2007; Luck & Hillyard, 1994a; Martin-Loeches, Hinojosa, & Rubia, 1999).

Unlike in the present study, Moher et al. (2014) did replicate Zhang and Luck’s observation of a feature-based attention effect on the P1. A notable difference between the present study and the other two studies is the number of stimulus presentations in each cell of the analyses. Neither of the other studies report exact numbers, but there appear to have been roughly 1,800 stimuli per cell in Zhang and Luck’s study, and roughly 800 per cell in Moher et al.’s study; considerably more than the 538 per cell in the present study. (It was necessary of us to use fewer stimulus presentations because of the introduction of WM load as an additional factor.) Thus, it is possible that my failure to replicate the P1 effect observed in the other two studies was due to my data having a relatively lower signal-to-noise ratio.

Despite having far fewer stimuli per cell than Zhang and Luck (2009), however, I did still have considerably more stimuli per cell than there were in other previous studies that have found early effects of feature-based attention using different paradigms. For example, Akyürek and Schubö (2013) found an effect of feature-based attention on the P1, N1, and N2 components, using only around 200 stimulus presentations per cell. This makes it even more noteworthy that none of the
three studies that have used Zhang and Luck’s paradigm found effects of feature-based attention on any component other than the P1.

Based on the discussion above, I argue that the lack of feature-based attention effects in the present study is due to some aspect of the experimental paradigm, rather than indicating that feature-based attention does not affect early perceptual processing. In the present paradigm, target events – dimming of the “attended” colour dots – are actually defined by the absence of the colour observers are supposed to be attending to. Thus, for example, when participants are monitoring the red-dot field, the target event they are required to detect is actually a brief period over which the attended dots become darker and less saturated. This is very different from other feature-based attention tasks, which typically require observers to search for objects that possess the target feature. This might have caused participants in the present experiment to use a search strategy different from that used in more typical feature-based attention tasks, and different from what is typically considered as feature-based attention (i.e., enhancement of neural responses to the target feature(s), and/or inhibition of neural responses to other features). With the benefit of hindsight, it might have been wiser to use a different feature-based attention task in the present experiment, and doing so may prove a more fruitful avenue for future research. For now, the question of whether early perceptual effects of feature-based attention are reduced under high WM load remains unanswered.
Chapter 5. Interactive effects of task set and working memory capacity on attentional capture
5.1. Introduction

In Chapter 3 I found information-updating WM load can reduce contingent capture as measured using the N2pc. This finding fits with the notion that selective attention and WM are both functionally and anatomically related constructs (e.g., Baddeley, 2012; Lavie et al., 2004). As discussed in Chapter 1, selective attention has been linked not only to WM load, but also to WM capacity. It has been argued that the relationship between WM capacity and selective attention is predominantly driven by the central executive component of WM, rather than the short-term memory (STM) components (Awh & Vogel, 2008; Cowan, Elliott, Saults, et al., 2005; Engle, 2002). This argument has been difficult to test directly. Although factor analyses support the notion that the central executive and STM components of WM are dissociable constructs (Engle, Tuholski, Laughlin, & Conway, 1999), no measures uniquely reflect the capacity of the central executive, without also reflecting STM capacity to some extent.

There is, however, a diverse body of indirect evidence that the relationship between WM capacity and selective attention involves the central executive. Behaviourally, WM capacity predicts performance on a variety of different tasks that ostensibly require executive control rather than STM, including antisaccade tasks (Kane et al., 2001), Stroop tasks (Kane & Engle, 2003; Long & Prat, 2002), Eriksen flanker tasks (Redick & Engle, 2006), and dichotic listening tasks (Conway et al., 2001). There is also electrophysiological evidence that high-WM capacity individuals have a superior ability to exclude task-irrelevant distractors from gaining access to WM, as opposed to having a larger STM capacity (Vogel et al., 2005). Neuroimaging and neurostimulation studies in humans and invasive recordings in monkeys suggest that this control of access to WM involves the prefrontal cortex (McNab & Klingberg, 2008; Postle et al., 2006; Rainer et al., 1998), just as has been found for other aspects of executive control (Gazzaley & Nobre, 2012). The notion that it is the central executive component of WM capacity that relates to selective attention nicely dovetails with my WM load observations from Chapter 3. Recall that I found that contingent capture was influenced by information-updating WM load (which arguably involves the central executive), but not digit rehearsal WM load (which arguably involves only STM).

To date, no published study has examined the relationship between information-updating WM capacity and the contingent capture effect. Fukuda and Vogel (2011) have, however, investigated the relationship between visual short-term memory (VSTM) capacity and contingent capture. I discussed this study in detail in Chapter 1. To briefly recap, these authors had participants search for target items of a specific colour in search arrays that were sometimes preceded by distracting
flanker items of either the target colour (TC) or a non-target colour (NTC). To measure contingent capture, target RTs were compared between the TC and NTC flanker conditions. To measure recovery from contingent capture, the authors varied the SOA between the flanker item and target array, and looked at the time-course of the contingent capture effect as SOA increased. VSTM capacity was measured using a separate change detection task (Luck & Vogel, 1997). High- and low-VSTM capacity groups displayed the same magnitude of contingent capture effect at 0 ms flanker-target SOA, suggesting that VSTM capacity does not influence the initial contingent capture of attention. In contrast, there was an effect of VSTM capacity at an intermediate SOA of 150 ms, such that high-VSTM capacity individuals appeared to have recovered from contingent capture more by this stage than low-VSTM capacity individuals. As well as contingent capture, Fukuda and Vogel looked at stimulus-driven capture by comparing RTs between the NTC flanker condition and a no flanker condition. Unlike contingent capture, they found that VSTM capacity had no effect on the time-course of stimulus-driven capture. These patterns of results were then replicated in a different paradigm, using ERPs evoked by visual probe stimuli to track the locus of spatial attention over time. Fukuda and Vogel’s findings suggest that, although the VSTM component of WM capacity does not influence initial contingent capture, it does influence the time-course of subsequent disengagement once contingent capture has taken place.

This chapter reports on the final experiment in my PhD, in which I tested whether individual differences in WM capacity are related to individual differences in contingent capture. I measured contingent capture in the same sustained monitoring task I used in Chapters 2 and 3, with the same behavioural (RT) and electrophysiological (N2pc) indices of attentional capture. I took three separate measures of WM capacity, with distinct predictions for each measure. The first was a measure of information-updating WM capacity, for which I selected the same n-back task I used to manipulate WM load in Chapter 3. In line with my previous observation that increasing information-updating WM load reduced contingent capture, I predicted that information-updating WM capacity would correlate with contingent capture. My second WM measure was a measure of VSTM capacity, for which I chose the same change detection task used by Fukuda and Vogel (2011). In line with their findings, I predicted that VSTM capacity would not correlate with initial contingent capture, but would correlate with the time-course of recovery from contingent capture. To allow me to measure recovery from contingent capture, I varied the SOA between the distractor and target items, and compared the behavioural interference associated with the different distractors across SOAs. As an additional, electrophysiological, measure of recovery from contingent capture I measured the Pd component, which is thought to reflect the disengagement of attentional resources from distractors (e.g., Sawaki et al., 2012; Sawaki & Luck, 2013). My third WM measure was a
task put forward by Wilhelm, Hildebrandt, and Oberauer (2013), which I argue involves both information-updating and VSTM. I predicted that performance on this task would correlate with both contingent capture and the subsequent disengagement from contingent capture.

5.2. Method

5.2.1. Participants

Thirty-six staff and students (29 female, aged between 19 and 45) from The University of Queensland, Australia, took part in this experiment. All participants reported normal or corrected-to-normal vision. The University of Queensland Behavioural & Social Sciences Ethical Review Committee approved all procedures. I obtained written informed consent from participants prior to each testing session. Participants were financially reimbursed at a rate of AU$15 per hour.

5.2.2. Stimuli and apparatus

Stimulus presentation and response recording were controlled using Cogent software (Cogent 2000 toolbox: FIL, ICN, and Wellcome Department of Imaging Neuroscience) in Matlab version 7.13 (www.mathworks.com). During the EEG session, visual stimuli were presented on an LCD monitor at a screen resolution of 1920 × 1080 pixels and a refresh rate of 144 Hz. Participants were seated at a viewing distance of 45 cm from the monitor, maintained using a chin rest. During the WM capacity assessment session, stimuli were delivered via a PC laptop.

5.2.3. Procedure

Each participant took part in two separate sessions. In the first session, participants completed the sustained monitoring task while I recorded their brain activity using EEG. In the second session, participants completed the three WM capacity measures. The order in which the three WM capacity measures were completed was counterbalanced across participants. The first session lasted for approximately 1.5 hours, and the second session lasted for approximately 1 hour.

Sustained monitoring task

The sustained monitoring task is illustrated in Figure 5-1. This task was very similar to the coloured bars search task used in Chapters 2 and 3. Participants covertly monitored random dot fields above or below fixation for red or green bars. Red or green distractor bars were presented within random dot fields to the left and right of fixation. Unlike in Chapter 3, there was no dual WM load task, and
each stimulus stream lasted for 80 s. To allow me to measure recovery from contingent capture behaviourally, distractor events could either appear simultaneously with attended events (as in my previous experiments), or appear 75 ms or 150 ms beforehand.

Figure 5-1 Sustained monitoring task. Participants fixated a central plus sign and covertly monitored dynamic stimulus streams above and below fixation for groups of either red or green bars (varied across blocks). Their task was to report whether detected target bars were oriented horizontally or vertically as quickly and accurately as possible. Groups of red or green bars were also presented within dynamic stimulus streams to the left and right of fixation, and served as distractors.

Participants completed 2 practice and 24 experimental streams. The target colour (red or green) alternated every 4 streams, with the specific order of colours counterbalanced across participants. During the practice but not experimental streams, correct responses to target bars were followed by a high-pitched beep, and incorrect responses were followed by a low-pitched beep. Participants were informed of their average hit rate and RT at the end of each block.
Continuous electroencephalogram (EEG) data were recorded using a BioSemi Active Two system (BioSemi, Amsterdam, Netherlands), with the same recording parameters used in my previous studies (see Section 3.1.2).

Offline EEG data analysis was performed using BESA (6.0; MEGIS Software GmbH, Gräfelfing, Germany) and a purpose-built Matlab script. The data for the scalp electrodes were re-referenced to the average of all 64 scalp electrodes, and subjected to a 0.1 Hz high-pass digital filter. Noisy channels, identified by visual inspection of the data, were replaced by a spherical spline interpolation of the voltages recorded at all other scalp electrodes (a maximum of 4 per participant). The data were then segmented into epochs from 100 ms before to 400 ms after the onset of each distractor event, with the average voltage in the 100 ms pre-stimulus interval serving as a baseline. Epochs in which the difference between the maximum and minimum voltage exceeded 120 µV at any channel were automatically rejected to remove epochs contaminated by blinks, eye movements and other artifacts. An average of 7% of epochs per participant were rejected for violating this criterion. The remaining epochs were then averaged together, separately for each combination of distractor type\(^{17}\) (target colour, TC; non-target colour, NTC), and distractor location (left, right). A 40 Hz low-pass digital filter was applied to the averaged data. Data were then collapsed across the two distractor locations by separately averaging together waveforms from contralateral electrodes (electrodes left of the midline for distractors on the right, and electrodes right of the midline for distractors on the left) and ipsilateral electrodes (electrodes right of the midline for distractors on the right, and electrodes left of the midline for distractors on the left). An average of 313 epochs contributed to each waveform for each participant and each distractor type.

Working memory capacity measures

I assessed information-updating capacity using an \(n\)-back task (Chatham et al., 2011). The basic procedure is illustrated in Figure 5-2a. Participants monitored a stream of white letters (RGB 255, 255, 255, presented in ‘Arial’ font, height \(\approx 2^\circ\), duration = 400 ms, SOA = 1000 ms). In separate blocks, participants had to detected either 2-back repetitions or 3-back repetitions. Whenever they detected a target repetition, they had to press the space bar on a keyboard. Each block consisted of 40 letters, and included 5 target repetitions. Participants completed 1 practice and 7 test blocks on

\(^{17}\) Note that there is no “no distractor” condition in the EEG analyses, as there should not be any lateralised activity (i.e., the N2pc and Pd) evoked when there is no lateralised stimulus present.
the 2-back task, followed by 1 practice and 7 test blocks on the 3-back task. The first letter of a repetition could not appear before the third letter of the stream, and also had to appear at least 1 letter after the second letter of any earlier repetitions. The specific identities and ordering of the letters in each stream were identical for each participant, to remove these possible sources of variance in participants’ capacity estimates.

Figure 5-2 Paradigms for the WM capacity tasks. (a) N-back task. Participants monitored a letter stream for either 2-back repetitions (when a letter is presented that was also presented 2 letters earlier) or 3-back repetitions (when a letter is presented that was also presented 3 letters earlier). (b) Change detection task. Participants had to hold the colours and locations of a set of squares (4, 6, or 8) in memory, and then decide whether a probe square subsequently presented at one of the previously occupied locations had changed colour or not. (c) Location tracking task. Participants were presented with a series of coloured squares in random locations and order, and then at an unpredictable point in time had to recall the location each colour had appeared in most recently. There could be 3, 4, or 5 different colours to keep track of during each trial.
I assessed VSTM capacity using the same change detection task employed by Fukuda and Vogel (2011). The basic procedure is illustrated in Figure 5-2b. On each trial, participants were presented with an array of either 4, 6, or 8 coloured squares (width and height ≈ 0.65°) for 150 ms, and had to hold each square’s colour and location in memory. Colours were randomly selected from 7 possibilities (white, RGB 255, 255, 255; red, RGB 255, 0, 0; blue, RGB 0, 0, 255; green, RGB 0, 245 0; black, RGB 0, 0, 0; yellow, RGB 200, 200, 0; and purple, RGB 150, 30, 250) without replacement- aside from on trials involving arrays of 8 squares, in which a random one of the colours would be represented twice. The squares were randomly located within an imaginary box approximately 9.8° wide and 7.3° high, with the constraint that the centre of each square was at least 2° away from the centre of all other squares present. Squares were presented against a gray background (RGB 127, 127, 127). After a retention interval of 900 ms, a single probe square was presented at one of the previously occupied locations, and the participant made an un-speeded response as to whether the probe square was the same colour as the square that had previously occupied that location. The colour of the probe square was the same as the corresponding square in the memorised array on half of the trials. On the other half of trials, the colour of the probe square was randomly selected from the remaining 6 possible colours. Correct responses were followed by a high-pitched beep, and incorrect responses were followed by a low-pitched beep. The memory array for the next trial was presented 500 ms after the participant’s response. Participants completed 6 practice and then 60 test trials for each of the three possible array sizes. The order in which the array sizes were completed (4, 6, 8), as well as the colours and locations of every single square presented were identical for each participant, to remove these possible sources of variance in participants’ capacity estimates.

My third WM measure was a location tracking task put forward by Wilhelm et al. (2013). The basic procedure is illustrated in Figure 5-2c. Coloured squares (width and height ≈ 1.3°) were presented one at a time within a 3 × 3 grid (black lines, RGB 0, 0, 0, line thickness ≈ 0.05°). Participants were instructed to keep track of where each colour had appeared most recently. Over the course of a trial there could be 3, 4, or 5 different colours presented, giving rise to 3 difficulty levels. The colours used in each trial were randomly selected without replacement from 5 possibilities (red, RGB 255, 0, 0; blue, RGB 0, 0, 255; green, RGB 0, 245 0; yellow, RGB 200, 200, 0; and purple, RGB 150, 30, 250). The selected colours were presented in random order, with each colour appearing an unpredictable number of times (between 2 and 5) during each trial. Each square was presented for 2400 ms during the 3-colour trials, and 2800 ms during the 4- and 5-colour trials. There was a fixed inter-stimulus interval (ISI) of 500 ms between consecutive coloured squares. At the end of the trial, participants were prompted to click in the location they remembered each colour appearing in most
recently using a computer mouse. Participants completed 8 test trials for each difficulty level. The order in which the difficulty levels were completed (3, 4, 5), as well as the colours and locations of every single square presented were identical for each participant, to remove these possible sources of variance in participants’ capacity estimates. This task requires participants to keep a set of locations in memory, as required in the VSTM change detection task, and also to update that set of locations over time, as in the information-updating n-back task. As such, I anticipated that performance on this task would reflect both VSTM and information-updating capacity.

5.3. Results

All statistical tests were conducted with a two-tailed alpha level of .05. Mauchly’s Test of Sphericity was applied to all within-subjects F tests. Greenhouse-Geisser epsilon adjustments were made to degrees of freedom for these F tests wherever the assumption of sphericity was untenable. Unadjusted degrees of freedom are reported for all F tests. Data from two participants were excluded from the analyses reported below for obtaining negative K scores on the change detection task (see below). Adding these two participants back into the analysis did not change the overall pattern of results.

5.3.1. Working memory capacity measures

To estimate information-updating capacity based on the n-back task, I first calculated a d’ score for each difficulty level (2-back, 3-back) by defining correct responses to target repetitions as hits and incorrect responses to non-repetitions as false alarms. To avoid infinite d’ scores, hit rates of 100% were adjusted to 97.14% ([n trials-1]/n trials) and false alarm rates of 0% were adjusted to 0.41% (1/n trials). There were 6 instances of hit rates of 100%, and 3 instances of false alarm rates of 0%. There were no instances of hit rates of 0% or FA rates of 100%. I then averaged these scores across the two difficulty levels to yield a single d’ score per participant. The mean averaged d’ score was 3.20 (SD = 0.66). The range was from 1.97 to 4.43. To assess the reliability of this measure, I calculated two additional estimates of d’ per participant using only the odd or only the even numbered trials from each condition. The Spearman-Brown corrected correlation between these two estimates indicated that the measure had significant split-half reliability (see Figure 5-3a).
To estimate VSTM capacity based on the change detection task, I first calculated separate K values for each array size using the standard formula $K = (H + CR - 1)N$, where $H$ is the hit rate, $CR$ is the correct rejection rate, and $N$ is the array size (Cowan, 2001). I then averaged these values across the three array sizes to yield a single K score per participant. The mean averaged K score was 2.1 ($SD = 0.84$). The range was from 0.5 to 3.9. These results are comparable to those reported by Fukuda and Vogel (2011), who observed a mean K score of 2.4 ($SD = 0.82$, range = 1.0 to 4.2). The Spearman-Brown corrected correlation between individuals’ K scores on the odd versus even numbered trials indicated that the measure had significant split-half reliability (see Figure 5-3b).

To estimate visual information-updating capacity based on the location tracking task, I calculated the accuracy (proportion of correctly recalled locations) across all trials. The mean accuracy was 72.9% ($SD = 11.2$%), which is comparable to the previous study by Wilhelm et al. (2013), who reported a mean accuracy of 74% ($SD = 15$%). The range of accuracies was from 47.2% to 95.8%. The Spearman-Brown corrected correlation between individuals’ accuracy on the odd versus even numbered trials indicated that the measure had significant split-half reliability (see Figure 5-3c).
5.3.2. Sustained monitoring task

Behavioural results

Figure 5-4 displays mean hit rates (panel a) and RTs (panel d) for each combination of distractor-target SOA (0 ms, 75 ms, 150 ms) and distractor type (none, TC, NTC). To examine the effects of SOA and distractor type on behaviour at the whole group level, I subjected hit rates and RTs to separate $3 \times 3$ within-subjects ANOVAs. Each participant was exposed to 48 target events for each of the nine cells in these analyses. Target events to which participants responded incorrectly were excluded from the RT analysis. For the whole group hit rate analysis, there was no significant main effect of SOA, $F(2,66) = 2.39, p = .100$, or distractor type, $F(2,66) = 1.48, p = .234$, and no interaction between the factors, $F(4,132) = 0.05, p = .995$.

Figure 5-4 Behavioural results for the sustained monitoring task. (a) Mean hit rates as a function of distractor-target SOA and distractor type. Error bars represent within-subjects standard errors of the means (Cousineau, 2005). (b) Stimulus-driven capture costs calculated as the difference in hit rates between the no distractor and NTC distractor conditions for each SOA. The mean difference score for each SOA is indicated by a blue horizontal line. Individual scores are represented by ‘x’ marks, which are spread out horizontally when multiple individuals obtained the same scores. (c) Contingent capture costs calculated as the difference in hit rates between the TC and NTC distractor conditions for each SOA. (d) Mean RTs as a function of SOA and distractor type. (e) Stimulus-driven capture costs calculated as the difference in RTs between the no distractor and NTC distractor conditions for each SOA. (f) Contingent capture costs calculated as the difference in RTs between the TC and NTC distractor conditions for each SOA.
For the whole group RTs analysis (Figure 5-4d), a significant main effect of SOA, $F(2,66) = 29.72$, $p < .001$, $\eta_p^2 = .474$ was qualified by a significant interaction between the two factors, $F(4,132) = 8.24$, $p < .001$, $\eta_p^2 = .200$. This interaction was driven by a significant effect of distractor type at 0 ms SOA, $F(2,66) = 14.07$, $p < .001$, $\eta_p^2 = .299$, but not at 75 ms SOA, $F(2,66) = 0.99$, $p = .377$, or 150 ms SOA, $F(2,66) = 0.20$, $p = .817$. At 0 ms SOA, relative to the no distractor baseline ($M = 623$ ms, $SE = 11$ ms), RTs were significantly increased in the presence of TC distractors ($M = 644$ ms, $SE = 12$ ms), $t(33) = 5.24$, $p < .001$, but not NTC distractors ($M = 629$ ms, $SE = 11$ ms), $t(33) = 1.45$, $p = .156$. There was also a significant difference in RTs between the TC and NTC distractor conditions, $t(33) = 3.53$, $p = .001$. These behavioural results are consistent with my previous findings reported in Chapters 2 and 3, in which I also found RTs to targets to be selectively slowed by simultaneously presented task-relevant distractors. Interestingly, this behavioural interference appears to be completely eliminated if the distractor is presented 75 or 150 ms earlier than the target; at least when then group of participants is considered as a whole.

As done by Fukuda and Vogel (2011), I then converted the behavioural results into separate measures of stimulus-driven capture and contingent capture costs. Following on from the previous study, I defined stimulus-driven capture costs as the difference in hit rates and RTs between the no distractor and NTC distractor conditions at each SOA. Individual scores for stimulus-driven capture costs are plotted in Figure 5-4b (hit rates) and Figure 5-4e (RTs). Also following on from Fukuda and Vogel, I defined contingent capture costs as the difference between TC and NTC distractor conditions at each SOA. Individual scores for contingent capture costs are plotted in Figure 5-4c (hit rates) and Figure 5-4f (RTs). It is these individual difference scores that are correlated with the WM capacity measures in Section 5.3.3.

**ERP results**

Figure 5-5a displays the grand average contralateral minus ipsilateral difference waveforms associated with TC and NTC distractors at electrodes PO7/8, collapsed across all analysed participants. I took two separate approaches to calculating N2pc and Pd amplitudes. First, I took the traditional approach of simply calculating the mean amplitude across a specified time window that appears to contain the component of interest (e.g., Gaspar & McDonald, 2014; Hickey et al., 2009; Sawaki & Luck, 2010). Based on visual inspection of the grand average waveforms, I selected 180 – 260 ms post stimulus onset for the N2pc analysis, and 260 – 400 ms post stimulus onset for the Pd analysis (shaded grey in Figure 5-5a). Mean amplitudes across these two time windows are depicted in Figure 5-5b, separately for each distractor type. Both distractor types evoked a statistically
significant N2pc [TC, $t(33) = 8.20, p < .001$; NTC, $t(33) = 5.49, p < .001$], and also a statistically significant Pd [TC, $t(33) = 6.66, p < .001$; NTC, $t(33) = 6.41, p < .001$]. Consistent with my previous ERP results (see Chapter 3), there was a larger N2pc associated with TC distractors ($M = -2.09 \mu V, SE = 0.25 \mu V$) relative to NTC distractors ($M = -1.34 \mu V, SE = 0.25 \mu V$), $t(33) = 8.48, p < .001$. There was no statistically reliable difference in Pd amplitudes between TC ($M = 1.38 \mu V, SE = 0.21 \mu V$) and NTC ($M = 1.21 \mu V, SE = 0.19 \mu V$) distractors, $t(33) = 1.36, p = .183$. There was no significant difference between TC and NTC distractors in the HEOG data over the N2pc time window, $t(33) = 1.12, p = .273$, suggesting that the observed effect of distractor type on the N2pc was not a consequence of lateral eye movements toward the distractor location.

Figure 5-5 Mean amplitude ERP results. (a) Grand average contralateral minus ipsilateral difference waveforms associated with the distractors at electrodes PO7/8. The shaded boxes indicate 180 – 260 ms post stimulus onset and 260 – 400 ms post stimulus onset, the time windows used for the mean amplitude N2pc and Pd analyses, respectively. (b) Mean N2pc and Pd amplitudes calculated by averaging across the shaded time windows, separately for each distractor type. (c) Stimulus-driven capture costs defined as the amplitude associated with NTC distractors for each component. The mean amplitude for each component is indicated by a blue horizontal line. Individual scores are represented by ‘x’ marks. (d) Contingent capture costs calculated as the amplitude difference between the TC and NTC distractors for each component. Note that negative voltages are plotted upwards on all axes.

To express these mean amplitude values as measures of stimulus-driven capture costs, I simply took each individual’s amplitude for the NTC distractors, separately for each component (see Figure 5-5c). To express mean amplitudes as measures of contingent capture costs, I calculated the amplitude...
difference between TC and NTC distractors for each component (see Figure 5-5d). Like the behavioural difference scores, these stimulus-driven and contingent capture costs are correlated with the WM capacity measures in Section 5.3.3.

I then used a second “summed area” approach to calculating N2pc and Pd amplitudes proposed by Sawaki et al. (2012). These authors point out that the time windows used in traditional mean amplitude analyses are typically based on visual inspection of the grand average waveform, collapsed across all participants and conditions. Although time windows selected in this way may adequately reflect the grand averaged data, they do not necessarily adequately reflect the waveforms associated with each participant or each condition. Figure 5-6a provides a visual illustration of this point. This panel plots the difference wave associated with the TC distractor for one of the 36 participants in this experiment. The time windows used for the mean amplitude analyses in the previous paragraphs are indicated by dashed vertical lines. It is clear the contralateral negativity in this difference wave that would normally be referred to as the N2pc appears to begin much earlier than the beginning of the time window selected for the mean amplitude N2pc analysis, and appears to have ended substantially before the end of this time window. To allow for such variations in the latency of the N2pc and Pd components, Sawaki et al. (2012) suggested taking a very broad time window – 100 to 400 ms post stimulus onset – and defining the N2pc amplitude as the summed negative area within that window, and the Pd amplitude as the summed positive area within that window. The negative and positive areas over this broad time window are shaded grey in Figure 5-6a. Mean N2pc and Pd amplitudes calculated using Sawaki et al.’s summed area approach are presented in Figure 5-6b, separately for each distractor type.
Figure 5-6 Summed area ERP results. (a) Contralateral minus ipsilateral difference waveform associated with the TC distractor at electrodes PO7/8 for one example participant. The time windows used for the mean amplitude N2pc and Pd analyses (180 – 260 ms and 260 – 400 ms post stimulus onset, respectively) are indicated in this plot by dashed vertical lines. Notice that they do not appear to do a very good job of capturing the N2pc component for this participant. Using the summed area ERP approach proposed by Sawaki et al. (2012), this participant’s N2pc amplitude for this distractor type is calculated as the sum of all negative area(s) between 100 and 400 ms post stimulus onset (the grey shaded area above the x axis in this plot), and the Pd amplitude is calculated as the sum of all positive area(s) between 100 and 400 ms post stimulus onset (the grey shaded areas below the x axis in this plot). (b) Mean summed area N2pc and Pd amplitudes across all participants, separately for each distractor type. (c) Stimulus-driven capture costs defined as the amplitude associated with NTC distractors for each component. (d) Contingent capture costs calculated as the amplitude difference between the TC and NTC distractors for each component. Note that negative voltages are plotted upwards on all axes.

As pointed out by Sawaki et al. (2012), because their summed area method divides the data into the two components by grouping together all the data points of the same valence, N2pc and Pd amplitudes calculated using this method are statistically biased away from zero. As such, one-sampled comparisons between the amplitude of one of these components and zero are inappropriate. Comparisons between the two different conditions, however, are not similarly biased to being non-zero. Thus, it is still reasonable to compare TC and NTC distractors in terms of the component amplitudes calculated using this method. Encouragingly, doing so yields the same pattern of results I observed using the traditional approach. Once again, there was a significance difference in N2pc amplitudes, \( t(33) = 6.13, p < .001 \), such that TC distractors evoked a
significantly larger N2pc ($M = -214 \, \mu V.ms$, $SE = 27 \, \mu V.ms$) than NTC distractors. And once again, there was no significant difference in Pd amplitudes between TC ($M = 264 \, \mu V.ms$, $SE = 28 \, \mu V.ms$) and NTC distractors, $t(33) = 1.06, p = .298$. Thus, both approaches to calculating N2pc and Pd amplitudes indicated that at the whole group level, there was an effect of task set on the N2pc, but no similar effect of task set on the Pd.

As with the N2pc and Pd amplitudes calculated using the traditional approach, I converted the summed area amplitudes into separate measures of stimulus-driven and contingent capture costs. Again, stimulus-driven capture costs were defined as the amplitudes associated with the NTC distractors for each component (see Figure 5-6c), and contingent capture costs were defined as the difference in amplitude between TC and NTC distractors for each component (see Figure 5-6d). These attentional capture costs are correlated with the WM capacity measures in Section 5.3.3.

5.3.3. Correlations between working memory capacity and attentional capture

We come now to the primary analyses of interest in the present study. To test for effects of WM capacity on attentional capture, I calculated the correlations between, on the one hand, performance on each of the three WM capacity measures, and on the other hand, each of the 20 measures of attentional capture (12 behavioural measures: hit rates and RT effects at each SOA, separately for stimulus-driven and contingent capture; and 8 electrophysiological measures: N2pc and Pd amplitude effects, calculated using the two different methods, separately for stimulus-driven and contingent capture). The results of these correlation analyses are presented in Figures 5-7 through 5-14. In each of the plots in these figures, the measure of WM capacity is plotted on the $x$-axis, and the measure of attentional capture is plotted on the $y$-axis. Somewhat remarkably, not a single one of these 60 correlations was statistically significant, even at an uncorrected alpha level of .05. Thus, I found no evidence for any relationship between any aspect of WM capacity and either stimulus-driven or contingent attentional capture.
Figure 5.7 Correlations between WM capacity and stimulus-driven capture as measured by hit rates.
Figure 5.8 Correlations between WM capacity and contingent capture as measured by hit rates.
Figure 5-9 Correlations between WM capacity and stimulus-driven capture as measured by RTs.
Figure 5-10 Correlations between WM capacity and contingent capture as measured by RTs.
Figure 5-11 Correlations between WM capacity and stimulus-driven capture as measured by mean amplitude ERPs.
Figure 5-12 Correlations between WM capacity and contingent capture as measured by mean amplitude ERPs.
Figure 5-13 Correlations between WM capacity and stimulus-driven capture as measured by summed area ERPs.
Figure 5-14 Correlations between WM capacity and contingent capture as measured by summed area ERPs.
5.4. Discussion

In this experiment I tested whether individual differences in two aspects of WM capacity (information-updating capacity and VSTM capacity) are related to individual differences in contingent capture. I found no relationship between any of the measures of WM capacity and any of the measures of attentional capture. All of the WM capacity measures were highly reliable and I observed good spreads of scores on them, comparable to or larger than those reported in previous research using the same measures. The number of participants in my experiment was comparable to or larger than many other studies that have found statistically significant relationships between WM capacity and other aspects of attentional control (e.g., Conway et al., 2001; Fukuda & Vogel, 2011; Vogel et al., 2005). I took both behavioural and electrophysiological measures of attentional capture and subsequent disengagement in a paradigm I previously used to demonstrate a relationship between contingent capture and WM load, manipulated via an n-back task. Particularly surprisingly, individual performance on a very similar n-back task bore no relationship with the same measures of contingent capture. My present findings suggest that individual differences in WM capacity do not influence the ability to bias attentional capture toward objects with task-relevant features. This is somewhat surprising given previous research that has linked WM capacity to other executive control functions, such as selectively attending to task-relevant stimuli in Stroop tasks (Kane & Engle, 2003), and flanker tasks (Redick & Engle, 2006).

There is even evidence that WM capacity can influence voluntary feature-based attention if the object falls within the current focus of voluntary spatial attention. Bengson and Mangun (2011) used a modified version of a Posner cueing task (Posner, 1980) in which participants were cued to both the spatial location (left or right of fixation) and orientation (vertical or horizontal) of an upcoming target grating whose spatial frequency (high or low) they had to report. Both cue types were 87% predictive, and participants could be validly cued to the location, orientation, both, or neither. Performance on the cueing task was then correlated with performance on an O-Span task (Turner & Engle, 1989), a measure of information-updating WM capacity that involves building up a series of letters in memory but solving a math equation between each letter. WM capacity significantly predicted the magnitude of the orientation cue validity effect, but only on trials in which the spatial cue was valid. Bengson and Mangun explained their findings within the framework of feature integration theory (Treisman & Gelade, 1980), which argues that the key role of attention in perception is to integrate and bind featural information across a series of initially independent dimensions, e.g., location, colour, orientation, spatial frequency. Bengson and Mangun
suggested that WM capacity only correlates with attentional tasks that require the integration of information across multiple dimensions in their case, location and orientation.

Other lines of research also support the more general notion that the relationship between WM and attention might be limited to attentional tasks that require the updating or integrating of new information. Woodman et al. (2007) had participants detect the presence of a Landolt C of a specific orientation from within an array of differently-oriented distractors. If the target orientation changed on every trial, increasing WM load by presenting the search array during the retention interval of a coloured square change detection task significantly impaired visual search performance. In contrast, if there was a constant target orientation on every trial, increasing WM load had no effect on visual search performance (see also Woodman et al., 2001). Woodman et al. explained these results by arguing that with a variable target identity, attentional resources are required to maintain and update a target template for the visual search task. Performing the change detection task also requires attentional resources to maintain and update representations of the coloured squares (sometimes referred to as object files; Treisman, 1988), and so performing both tasks at once leads to competition for attentional resources. With a constant target identity, the prefrontal cortex – the presumed neural locus of competition between the two tasks – gradually ceases to be required for maintaining and updating a target template, which is transferred to other areas of cortex. This argument fits well with a study that found monkeys with prefrontal cortex lesions were impaired on visual search tasks when target identity changed on each trial, but with practice could perform comparably to monkeys with intact prefrontal cortices when target identity remained constant (A. F. Rossi, Bichot, Desimone, & Ungerleider, 2001).

Although the present results suggest a lack of relationship between contingent capture and three measures of WM capacity, it remains possible that contingent capture correlates with other aspects of WM capacity not captured by the three measures employed here. Kane, Conway, Miura, and Colflesh (2007) argue that information-updating tasks such as the n-back reflect a fundamentally distinct component of WM capacity than what they refer to as ‘complex span tasks’, such as the previously described O-span (Engle, 2002) and reading span (R-span; Daneman & Carpenter, 1980) tasks. Kane et al. (2007) demonstrated reliable dissociations between performance on n-back and complex span tasks, and found they accounted for independent pools of variance in performance on measures of general fluid intelligence. These authors speculated that this difference may reflect the fact that tasks such as the n-back (and also the other two WM capacity measures I employed in the present study) only involve recognition memory processes, whereas complex span tasks require free recall of information. Future research would valuably extend on the present work by testing for
relationships between contingent capture and complex span tasks such as the O-span.

To summarise, although there are relationships between some aspects of WM and selective attention, this by no means generalises to all aspects of WM or all aspects of selective attention. Based on my findings from Chapter 3 and the research discussed in the previous two paragraphs, it seems that a relationship is more likely for aspects of WM and selective attention that involve either the dynamic updating of information, or the integration of information across multiple feature dimensions. A more general description of this pattern of observations is that the more two tasks require executive control, the more they will compete for shared resources in prefrontal cortex. In the present experiment, I found no relationship between individual differences in WM capacity and contingent capture. This pattern of results is in agreement with the findings of Woodman et al. (2007), who found that WM capacity only predicted the magnitude of a voluntary feature-based attention effect within the spotlight of spatial attention. (Recall that the distractor stimuli in the present sustained monitoring paradigm were always presented at ignored visual field locations.) Nevertheless, the lack of a relationship between contingent capture and performance on an n-back task was somewhat surprising given that in Chapter 3 I found performing an n-back task *concurrently* reduced contingent capture. One possible explanation is that the relationship between the n-back task and contingent capture only emerged when both tasks had to be performed concurrently, because under these conditions there was the additional requirement to actively coordinate resources between the two tasks.
Chapter 6. General discussion
The involuntary capture of attentional resources by stimuli in the environment was once thought to be an automatic process, affected only by the physical attributes of the capturing stimulus (e.g., Theeuwes, 1992). Against this assumption, the contingent capture hypothesis (Folk et al., 1992) argues that attentional capture is modulated by the particular visual features being looked for by an observer. According to several theories of attentional control (e.g., Lavie et al., 2004), the ability to bias attentional capture toward task-relevant features depends on similar neural resources as other executive control functions, such as WM. This thesis set out to investigate both the influence of feature-based task settings on attentional capture, and the extent to which this influence is related to WM. In a series of seven experiments, participants monitored visual stimulus streams for target items defined by a particular feature value (e.g., red). The extent to which distracting visual stimuli captured participants’ attention was quantified in terms of: (a) their influence on visual search performance, and (b) the ERPs associated with them. Distractors with the current target-defining feature value slowed responses to concurrently presented target items more than distractors with other feature values. This pattern of results is consistent with the contingent capture hypothesis that stimuli capture attention more strongly if they possess task-relevant features.

Proponents of the rapid disengagement hypothesis (Theeuwes, 2000) would, however, correctly point out that the greater behavioural interference associated with task-relevant distractors could also be due to differences in the speed at which attention can be disengaged from distractors, rather than differences in the extent to which they initially capture attention. To discriminate between these two competing explanations for the observed behavioural results, I also measured the distractor-evoked N2pc, an ERP component that reflects the extent to which a stimulus captures spatial attention to its location (Eimer & Kiss, 2010; Luck & Hillyard, 1994). Distractors with the current target-defining feature value evoked a larger N2pc than distractors with other feature values. This finding is once again consistent with the contingent capture hypothesis that internal task settings can influence attentional capture, and is also inconsistent with the stimulus-driven and rapid disengagement hypotheses that state that internal task settings do not influence attentional capture.

In Chapter 3 I investigated the relationship between contingent capture and WM by comparing the effect of feature-based task set on the distractor-evoked N2pc and behavioural interference between different levels of WM load. Taxing WM by means of a concurrent n-back task eliminated the influence of task set on the distractor-evoked N2pc, suggesting that increasing WM load compromised feature-based biases on attentional capture. This supports the emerging perspective that attention and WM are functionally linked, and depend on a shared pool of neural resources (e.g., Baddeley, 2012; Gazzaley & Nobre, 2012). The effect of WM load on contingent capture did
not generalise to all manipulations of WM load, however: A digit rehearsal task that required only information maintenance did not have a similar effect, suggesting that the information-updating element of the n-back WM manipulation was critical to its effect on contingent capture. These findings also support theoretical models (e.g., Chun, 2011; Daneman & Carpenter, 1980; Engle, 2002; Lavie et al., 2004) that argue that the link between selective attention and WM is driven primarily by the central executive component of WM, rather than the STM component(s). A previous study by Brisson et al. (2009) provides converging evidence that feature-based effects on attentional capture can be influenced by the load imposed on central executive processes. They found a smaller contingent capture effect on the distractor-evoked N2pc for distractors presented during the PRP, a period during which stimulus processing is compromised because of competition for central decisional resources (Tombu & Jolicoeur, 2003).

Future studies could further test the notion that the competition between WM and feature-selective attention arises at central stages of processing by examining whether WM load reduces contingent capture even when the WM load does not involve the processing of visual stimuli. For example, one could conduct an experiment very similar to Experiment 4 (Chapter 3) but with the n-back task performed on aurally rather than visually presented letters. Demonstrating that feature-based attention and WM tasks interfere with each other when they involve stimuli in different sensory modalities would strengthen the case that the competition between the processes arises in central, amodal brain areas because there would no longer be the possibility of competition during early sensory stages of processing. This logic was used in a previous study by Klemen et al. (2010) who found that increasing WM load via an auditory n-back task reduced the sensitivity of BOLD responses in the LOC to the contrast of distracting visual images, consistent with the notion that WM and selective attention compete for amodal central executive resources.

There is good evidence that the central executive control networks involved in feature-based attention and WM are located in prefrontal and parietal brain regions (Gazzaley & Nobre, 2012). With the behavioural and EEG-based measures used in the present thesis, it was not possible to specifically test the hypothesis that competition for resources in these brain regions were the cause of the observed effects of WM load on contingent capture. Future studies could investigate the neural basis of the effects observed here by employing measurement techniques with higher spatial resolution than the EEG and behavioural measures used in the present studies. For example, fMRI could be used to identify brain regions that respond preferentially to distractors with task-relevant features (as previously done by Serences et al., 2005; see Section 1.2.3. for details), and the magnitude of this feature-based attentional effect on BOLD responses could be compared between
different levels of WM load. The findings of the present work suggest an n-back task would be a
good choice as a WM load manipulation. In line with Lavie et al.’s (2004) cognitive load theory and
also the present findings, one would predict that increasing WM load should reduce the bias in
BOLD responses toward task-relevant distractors in both early visual cortex and higher-level
executive control regions identified by Serences et al. (2005). One would also predict that BOLD
responses in some of the same frontal and parietal executive control regions should scale with WM
load, consistent with the notion that the reduced effect of task set on sensory processing arose
because executive control resources were diverted to performing the WM task instead. Follow-up
studies using neurostimulation techniques (e.g., TMS or tDCS) could then target the frontal and
parietal brain areas whose activity was modulated by both feature-based task set and WM load. If
stimulating these areas altered the effects of feature-based task set and WM load on attentional
capture (as measured using behaviour, early visual ERPs, or BOLD responses), this would provide
direct causal evidence for their involvement in the resource competition that arises between feature-

Although the n-back WM load manipulations employed in Chapter 3 eliminated contingent capture
as indexed by the N2pc, they did not influence contingent capture as measured by RT. Distractors
with task-relevant features slowed RTs to a greater extent regardless of the concurrently imposed
WM load. Such a dissociation is not unprecedented; other studies (e.g., Brisson et al., 2009; Töllner
et al., 2008) also found that effects apparent at the level of the N2pc were absent in behavioural
responses. These dissociations raise the question of whether the N2pc and RTs actually reflect a
common underlying process in contingent capture experiments. One point to bear in mind is that the
notion that any effect apparent in the distractor-evoked N2pc should also be apparent in behavioural
interference rests on the assumption that the N2pc reflects a shift in finite spatial attentional
resources away from one object (the target) and toward another (the distractor). There is some
evidence that this assumption might not be correct. For instance, Eimer and Grubert (2014) found
that the N2pc associated with a lateralised target item was unaffected by the temporal proximity of
a second target item on the vertical midline. This suggests that, although the presence of an N2pc
may indicate the capture of attention to one location, such capture does not necessarily prevent the
allocation of attentional resources to other locations at the same time. Further support for this
suggestion comes from my observations that task-irrelevant distractors often evoked a reliable N2pc
even when their presence had no effect on the speed at which observers could respond to
concurrently presented targets.
Additionally, as mentioned previously, behavioural measures such as interference with target responses cannot be considered direct indices of attentional capture as they reflect the end-point in a set of perceptual, decisional, and response processes. Thus, as discussed in Chapter 3, another possible explanation for the dissociation between N2pc and behavioural results observed here is that taxing WM not only compromised feature-based biases in early visual cortex, but also compromised other aspects of stimulus processing, such as the transfer of information from early visual cortex to later stages of processing. This possibility should be tested in future research by further investigating the processing stage(s) that are, and are not, affected by the interaction between feature-based attention and WM load. One option would be to measure ERP components subsequent to the N2pc, to more precisely pinpoint the stage at which the effect of WM load on contingent capture disappears. Other potential components of interest might include the P3 (or P300; Luck, 2005; Polich & Kok, 1995) as an index of allocation of attentional and memory resources to the distractors, and the CDA (Vogel et al., 2005; also referred to as the sustained posterior contralateral negativity, SPCN; Eimer et al., 2011) as an index of the extent to which the distractors go on to occupy VSTM.

To investigate the role of physical salience on attentional capture, in Experiment 3 I looked at the differences between coloured distractors and more salient onset distractors. Behaviourally, the task-irrelevant onset distractors had no effect on target RTs at either level of WM load, consistent with the notion that they failed to capture attention away from the target location. Electrophysiologically, there was no clear contralateral negativity in the “standard” N2pc time window, as illustrated in Figure 3-10. Interestingly, however, there was a much earlier contralateral negativity, during a time window in which no contralateral effects are apparent for the other distractor conditions. As illustrated in Figure 3-2, the contralateral negativity associated with the motion distractors in Experiment 1 also began earlier than that for the arguably less salient colour distractors. These observations are consistent with the notion that the speed of early stages of perception are modulated by stimulus salience (e.g., Luck, 2005).

The observations described above are in line with the suggestion of Hickey et al. (2010) that the speed at which attentional capture occurs is influenced by salience. Their suggestion was based primarily on two observations from an additional singleton paradigm in which observers searched for shape singleton targets that were occasionally accompanied by salient but task-irrelevant colour singleton distractors. First, colour distractors evoked an earlier N2pc when target responses were slow, consistent with the notion that when distractors captured attention quickly they delayed the allocation of attention to the target. Second, when the target and distractor were in opposite visual
fields there was a small negativity contralateral to the distracting colour singleton just prior to the negativity contralateral to the target, consistent with the notion that spatial attention briefly shifted to the distractor prior to shifting to the target location. McDonald et al. (2013) have challenged the findings of Hickey et al., arguing that a confound in their design meant that their distractors were not necessarily entirely task-irrelevant. Specifically, distractors never appeared in the same visual hemifield as the target, and as such might have been used to help guide search for the target. When McDonald et al. attempted to replicate Hickey et al.’s study without this confound, they failed to find any evidence for an influence of salience on the speed of attentional capture. Importantly, however, both of these previous studies suffer from an additional confound, namely that they involve a comparison between a distractor that requires no behavioural response and a target that requires a behavioural response. This confound is not present in the comparisons between colour distractors and onset and motion distractors in the present work. Thus, although they are only exploratory observations, the present findings of variability in N2pc onset latency might usefully contribute to the ongoing debate regarding the influence of stimulus salience on the speed of attentional capture. Future studies should more directly test for such an influence by systematically manipulating distractor salience under constant task conditions, and measuring N2pc onset latency as an index of the speed of attentional capture.

In Chapter 4 I went on to test whether competition between feature-based attention and WM load extends down to even earlier stages of perceptual processing than those reflected by the N2pc. Unexpectedly, there was no effect of either feature-based attention or WM load on early visual ERPs associated with distractors at task irrelevant locations. This stands in contrast to a number of previous studies that have found effects of both feature-based attention (W. W. Zhang & Luck, 2009) and WM load (Rose et al., 2005) on distractor-evoked early visual ERPs. One possible explanation is that these variables had no effect on distractor-evoked early visual ERPs in the present studies due to a lack of statistical power. For example, in Chapter 4 I was only able to include roughly one-third of the trials of W. W. Zhang and Luck (2009), because I had to incorporate the further factor of WM load. This likely led to a lower signal-to-noise ratio. Similarly, the effect of WM load on distractor-evoked early visual ERPs observed by Rose et al. (2005) was not on mean N1 amplitudes, but on the extent to which N1 amplitudes changed with decreasing image visibility, which might be a more sensitive index of distractor processing than mean amplitudes. As discussed in Section 4.4, another factor that might have contributed to the lack of effects on distractor-evoked early visual ERPs in the present work is the task used to manipulate feature-based task set. Recall that in the feature-based attention task used in Chapter 4 (developed by Zhang & Luck, 2009) participants effectively monitored for the absence of the “attended”
feature value, as target events were defined by luminance changes in the attended objects. In contrast, most other feature-based attention tasks require participants to monitor for the presence of objects with the target-defining feature. Given that the single experiment reported in Chapter 4 represents the only study that has tested for an interaction between feature-based attention and WM on early visual ERPs, I suggest it would be prudent to conduct a conceptual replication using a different, more typical, feature-based attention task. One possibility would be to modify Zhang and Luck’s (2009) paradigm so that rather than monitoring for brief luminance decrements in a target-coloured dot field, participants monitor for brief appearances of target-coloured dots. An alternative would be a modified version of the paradigm used in Chapter 3 of this thesis. Note that insufficient trial numbers precluded an analysis of early visual ERPs in the experiments reported in Chapter 3. This is because, unlike contralateral effects such as the N2pc, early visual ERPs such as the P1 cannot simply be collapsed across left and right distractor locations or upper and lower target locations. This issue could be overcome, however, by modifying the paradigm to include only one distractor location and one target location.

Previous research has indicated that effects of WM and feature-based attention can vary between spatially attended and unattended locations (Bengson & Mangun, 2011). To briefly recap, Bengson and Mangun (2011) found a correlation between WM capacity and the effectiveness of valid feature-based cues presented during a selective attention task, but only within the current locus of spatial attention (see Section 1.3.2 for details). This might explain the difference in behavioural results between the present experiments and those reported by Lavie and De Fockert (2005). Recall that in the present experiments distractors only appeared at spatially unattended locations (i.e., within the stimulus streams to the left and right of fixation, that observers knew would never contain a target). Under these conditions, increasing WM load did not change the behavioural interference associated with task-irrelevant NTC distractors (see Section 3.2). By contrast, distractors in the additional singleton paradigm employed by Lavie and De Fockert (2005) always appeared at spatially attended locations (i.e., within the visual search array; see Section 1.3.2). Under these conditions, the same WM load manipulation as was used in Experiment 2 increased the behavioural interference associated with task-irrelevant additional singletons. To test whether this difference in findings is related to spatial attention, and also to test whether the effects reported here generalize to spatially attended locations, follow-up studies could investigate whether spatial attention mediates the observed interaction between WM load and feature-based attention reported in Chapter 3. To manipulate whether distractors appeared at spatially attended locations in the present paradigm, participants could be tasked with monitoring for targets in only the upper and lower boxes in one condition (as in the present studies), or monitoring for targets in all four boxes.
in another condition. Distractor objects could be changed from bars into squares such that they would still be clearly discriminable from targets.

Another factor that has previously been found to influence feature-based attention is the extent of competition between attended objects and other objects nearby. For example, W. W. Zhang and Luck (2009) found that target-coloured distractors only evoked a larger P1 than non-target-coloured distractors when the coloured moving dot field observers had to monitor was presented at the same time and location as a different coloured moving dot field. There was no effect of distractor colour on the P1 when the monitored dot field was presented in isolation. Such findings can be explained within the framework of Desimone and Duncan’s (1995) biased competition model, which argues that mechanisms of selective attention are only employed when task-relevant objects cannot be successfully identified by other means, for example by virtue of being the only objects physically present. This assertion is supported by single-cell recording studies that have demonstrated that spatial attention modulates firing rates of cells in early visual cortex when distractor stimuli are presented in close spatial proximity to the target location, but not when distractor and target locations are further apart (e.g., Moran & Desimone, 1985). Follow-up studies to the present work could similarly examine the influence of local competition on the effects observed here by varying the distance between the attended and unattended stimulus streams. Alternatively, local competition could be introduced at the attended locations by presenting only a portion of the bars in the target colour during target events, while the other bars remain grey or perhaps change to a different non-target colour.

As with previous studies of attentional capture, the dependent measures employed in this thesis were measures of central tendency, such as the mean RT observed under certain conditions. Research in other fields, however, has demonstrated that changes in RTs can emerge not only as mean differences, but also as differences in RT variability. For example, increased RT variability on a range of sustained attention tasks has been associated with a variety of brain pathologies including attention-deficit hyperactivity disorder (ADHD; Castellanos et al., 2005; Johnson et al., 2007), schizophrenia (Schwartz et al., 1989), and traumatic brain injury (TBI), particularly involving damage to the frontal lobes (Stuss, Murphy, Binns, & Alexander, 2003; Stuss et al., 1989). Such findings have been interpreted as evidence that increased RT variability results from impairments in the ability to maintain a constant level of top-down attentional control over time (Barkley, 1997). Bellgrove, Hester, and Garavan (2004) tested this possibility in healthy controls using a Go/No-go response inhibition task in which participants made a simple button response to each stimulus in a regular pattern (Go trials; e.g., the alternating letters A B A B), but then had to inhibit a response if
the pattern was broken (No-go trials; e.g., the final letter in the sequence A B A A). RT variability on this task was positively correlated with the number of failures to successfully inhibit a response on the No-go trials, and also with the level of BOLD activity observed during task performance in frontal and parietal brain areas implicated in executive control. The authors interpreted these findings as evidence that increased RT variability is associated with poorer cognitive control, and a greater need to recruit executive control networks during sustained attention tasks. Given these links between executive control and RT variability, future studies of links between feature-based attention and WM might benefit from testing for not only mean RT differences between conditions, but also differences in RT variability. Note that such analyses were not conducted on the present datasets because of relatively low trial numbers and relatively small sample sizes.

The response variability studies mentioned above all measured variability in behavioural responses. As the present work clearly demonstrates, however, mechanisms of executive control can also influence earlier perceptual stages of processing. Thus, another interesting avenue for future research might be to test whether manipulations of executive control also influence variability in perceptual stages of processing. For example, in the present work it might have been interesting to look for interactive effects of feature-based attention and WM not only on mean P1, N2pc, or Pd amplitudes, but also on trial-to-trial variability in the amplitudes of those components. 18 Similarly, future fMRI investigations could test whether feature-based attention and WM modulate not only mean BOLD responses (in both sensory cortex and higher level executive control regions) but also trial-to-trial variability in BOLD responses. Research such as this would usefully extend on the present work, and test the possibility that competition between executive control resources might lead to impairments not only in the ability to bias perceptual processing toward task relevant stimuli, but also in the ability to maintain such biases over time.

The experiments presented in thesis focused entirely on the interactive effects of feature-based attention and WM on distractor processing. There is, however, every reason to expect that these factors also have interactive effects on the processing of target objects. After all, the primary purpose of mechanisms of selective attention is arguably to facilitate the identification and processing of target objects. As such, another interesting follow-up to the present research would be to test whether the selective facilitation of target processing is also compromised under high WM

18 Note that estimating the amplitudes of ERP components at the single trial level is technically challenging because of very low signal-to-noise ratios (for details, see Cerutti, Baselli, Liberati, & Pavesi, 1987; Eichele et al., 2005; Huster, Debener, Eichele, & Herrmann, 2012; Quiroga & Garcia, 2003), and would likely require some changes to the paradigms used in the present studies.
load. One option for this investigation would be to measure early visual ERPs associated with target events in the sustained monitoring paradigm introduced here, and compare these between conditions of high and low n-back WM load. Note that the number of target presentations was kept relatively low in the present studies to ensure distractors were presented a sufficient number of times for the distractor-evoked N2pc analyses. As such, there were not enough target presentations for an analysis of target-evoked early visual ERPs. The present paradigm could, however, be modified to permit the measurement of target-evoked early visual ERPs by changing the relative proportions of target and distractor presentations. Additionally, the paradigm could be modified in future research to allow measurement of the target-evoked N2pc by switching the distractor and target locations such that targets appeared in the left and right stimulus streams and distractors appeared in the upper and lower stimulus streams.

The prefrontal cortical networks responsible for selective attention and WM (e.g., Awh et al., 2006; Gazzaley & Nobre, 2012) are also implicated in a wide variety of other cognitive and executive control functions. Measures of WM capacity correlate not only with performance on selective attention tasks (e.g., Kane et al., 2001), but also with performance on a diverse range of other tasks and outcome measures, including speaking and writing abilities, solving arithmetic problems, solving complex reasoning problems, and learning to write computer programs (Daneman & Merikle, 1996; Engle, Kane, et al., 1999; Kane & Engle, 2002). Neuroimaging studies have found that similar regions of prefrontal cortex are active during a variety of cognitive and problem solving tasks (Duncan et al., 2000; Gray, Chabris, & Braver, 2003). Further, patients with damage to prefrontal cortices are impaired on a variety of cognitive tasks, including problem solving, maze learning, and picture description (Duncan, 2001). Such observations have led some researchers to propose that the prefrontal cortex is the neural substrate for Spearman’s (1904) notion of a “general intelligence” factor that underlies performance on most cognitive tasks (Duncan et al., 2000; Gray et al., 2003; E. K. Miller & Cohen, 2001). From this perspective, the competition between feature-based attention and WM observed here should also extend to other cognitive and executive control functions. As such, another interesting avenue for future research would be to investigate whether other executive control functions interfere with each other and compete for shared prefrontal neural resources. This research could include other relatively “low-level” executive control processes such as spatially selective attention, task switching, response inhibition, and the ability to coordinate multiple tasks, and could also extend to “higher-level” executive control processes such as complex reasoning, procedural learning, and language tasks.
References


single-trial event-related potentials and functional MRI. *Proceedings of the National Academy of Sciences of the United States of America, 102*(49), 17798-17803. doi: 10.1073/Pnas.0505508102


Eimer, M., & Kiss, M. (2010a). The top-down control of visual selection and how it is linked to the n2pc component. *Acta Psychologica, 135*(2), 100-102. doi: 10.1016/j.actpsy.2010.04.010


Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex, 1*(1), 1-47. doi: 10.1093/cercor/1.1.1


Export Date 2 February 2012


Milner, B. (1963). Effects of different brain lesions on card sorting - role of frontal lobes. *Archives of Neurology, 9*(1), 90-.


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